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Comparison of three optical models and analysis of geometric parameters for parabolic trough solar collectors

Hongbo Liang, Shijun You, Huan Zhang*

School of Environmental Science and Engineering, Tianjin University, Tianjin, China

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ABSTRACT

A PTC (parabolic trough solar collector) focuses direct solar radiation reflected by the reflector onto a receiver located on its focal line. The solar flux distribution on the absorber is non-uniform generally, thus it needs to carry out optical simulation to analyze the concentrated flux density and optical performance. In this paper, three different optical models based on ray tracing for a PTC were proposed and compared in detail. They were proved to be feasible and reliable in comparison with other literature. Model 1 was based on MCM (Monte Carlo Method). Model 2 initialized photon distribution with FVM (Finite Volume Method), and calculated reflection, transmission, and absorption by means of MCM. Model 3 utilized FVM to determine ray positions initially, while it changed the photon energy by multiplying reflectivity, transmissivity and absorptivity. The runtime and computation effort of Model 3 were approximately 40% and 60% of that of Model 1 in the present work. Moreover, the simulation result of Model 3 was not affected by the algorithm for generating random numbers, however, it needed to take account of suitable grid configurations for different sections of the system. Additionally, effects of varying the geometric parameters for a PTC on optical efficiency were estimated. Effect of offsetting the absorber in width direction of aperture was greater than that in its normal direction at the same offset distance, which was more obvious with offset distance increasing. Furthermore, absorber offset at the opposite direction of tracking error was beneficial for improving optical performance. The larger rim angle ($\leq 90^\circ$) was, the less sensitive optical efficiency was to tracking error for the same aperture width of a PTC. In contrast, a larger aperture width was more sensitive to tracking error for a certain rim angle.

1. Introduction

A PTC (parabolic trough solar collector) focuses direct solar radiation reflected by the parabolic reflector onto a receiver located on its focal line. It is one of the most promising solar thermal applications, which can be applied to concentrated solar power, space heating, and heat-driven refrigeration, etc. Numerous scholars have established heat transfer models for a PTC to study and improve its thermal performance and stresses recently. Solar energy is the only energy source for the system, and the flux distribution on the absorber serves as a boundary condition for a PTC generally. Thus improvement of the optical performance is essential for improving its thermal efficiency. Many researchers have developed optical models and carried out the optical analysis.

Daly [1] proposed a backward ray tracing to determine flux distributions produced by parabolic and circular cylinder concentrators, characterized by tracing rays from an absorber point through the concentrator optics back to the sun. The model was well applied to calculate arbitrary shapes subject to imperfections and defocusing, however it was two-dimensional in the paper that can not consider flux distribution difference along the length. Jeter [2] derived a first integral of the concentrated flux distribution for trough concentrators. His model needed no elaborate special-purpose computer codes for implementation, nevertheless it required a more complicated mathematical derivation than MCRT (Monte Carlo Ray Tracing). Subsequently, a more realistic model [3] considering non-uniform solar luminance, imperfect reflection, absorption and transmission was presented to estimate practical collectors' optical efficiency. Sammouda et al. [4] investigated the concentrated energy distribution for paraboloid concentrator based on the Aparisi distribution law, presenting the irradiance distribution for different receiver surface positions and concentrated flux

* Corresponding author. Tel./fax: +86 22 2789 2626.
E-mail address: zhhuan@tju.edu.cn (H. Zhang).

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Nomenclature

W	aperture width (m)
f	focal length (m)
L	absorber length (m)
b	angle between the projection of incident ray on PTC cross section and normal of the aperture (y axis) (mrad)
c	angle between incident ray and cross section of PTC (mrad)
m	unit vector along the incident ray
n	normal unit vector of the parabolic trough
r	unit vector along the reflected ray
N_z	number of control volumes along the length of absorber
N_c	number of control volumes in the circumference of absorber
q	energy of each photon (W)
I	direct normal irradiance (W/m^2)
N_{ray}	total number of rays
N_l	number of control volumes along the length of parabolic trough
N_w	number of control volumes along the width of parabolic trough
$N_{\theta'}$	number of rays along solar radial direction
$N_{\varphi'}$	number of rays in the circumference of solar disk
e_{max}	maximum relative error (%)
e_{ave}	average relative error (%)
Q	energy absorbed by the absorber (W)
d_a	absorber outer diameter (m)
d_g	glass cover outer diameter (m)

Greek symbols

ξ_1~ξ_7	uniformly distributed random number between 0 and 1
θ'	deflection angle in the radial direction of solar disk (mrad)
φ'	tangential angle of solar disk (rad)
θ	angle between incident ray and normal of the aperture (y axis) (mrad)
φ	circle angle of the absorber (deg)
ρ	reflectivity of the parabolic reflector
τ	transmissivity of the glass
α	absorptivity of the absorber
τ_r	running time (s)
η_o	optical efficiency (%)
θ_s	solar angular radius (mrad)
ψ_{rim}	rim angle (deg)

Abbreviations

PTC	Parabolic trough solar collector
MCM	Monte Carlo Method
FVM	Finite Volume Method
MCRT	Monte Carlo Ray Tracing
LCR	Local Concentration Ratio

intensities. Buie et al. [5] proposed a sunshape model independent of geographic location, which is valuable for simulating solar concentrating systems. Grena [6] constructed a three-dimensional optical model with a ray-tracing recursive algorithm, which can simulate multiple reflections, refractions and different defects. The forms of a parabolic trough and a circular tube were fixed in that paper, however the method could be used for simulating other solar collectors. MCRT method was used in Ref. [7] to determine the non-uniform flux distribution of the absorber. Optical analysis based on this method is concise and efficient, while more details of the optical model were not introduced in that paper. Lu et al. [8] divided the receiver into two regions for uneven solar radiation, and Liang et al. [9] considered uniform flux distribution in the simulation. Their optical calculations were simpler and faster, which came down to lumped parameter method, whereas they can't show the detailed circumferential energy distribution of the absorber. Khanna et al. [10] analyzed not only circumferential but also axial flux expression of an absorber, taking into account the effect of bending additionally. Their optical model was more practical, and the analytical expression can reduce computational efforts for a designer. Cheng et al. [11] presented a general-purpose numerical method and unified MCRT code for simulating concentrating solar collectors. The model was useful and effective to determine parameters and optimizations theoretically, whereas the more real conditions, such as surfaces slope errors, should be studied further. Binotti et al. [12] extended the First-principle OPTical Intercept Calculation method to analyze the three-dimensional effects of PTC and calculate the intercept factors for non-zero incidence angles. Their method can evaluate the optical performance fast, and the first-principle optical treatment of error sources inherent in the method had high accuracy. Chen et al. [13] developed a two-dimensional optical model scattering PTC's arc length and solar subtending angle, luminance factor obtained by compressing Buie model with a diameter parallel to the generatrix of parabolic trough solar concentrator. And they considered the solar rays offset effect by the thickness of reflective mirror, which was ignored in many other researches.

In this paper, three diverse optical models were established for a PTC based on the ray tracing technology. They were different in initializing photon distribution and calculating reflection, transmission, and absorption. Their running times, computation efforts and characteristics were compared. It aimed to select a suitable model for analyzing and improving the optical performance of a PTC. Effects of varying the incident angle, rim angle and aperture width as well as offsetting the absorber tube (not on the focal line of a PTC) on optical efficiency were investigated further, which were essential for designing and optimizing the PTC's geometric parameters in the future.

2. Optical models and methodologies

As shown in Fig. 1, a PTC mainly consists of the absorber tube, glass cover and reflector. The optical model of a PTC aims to analyze the concentrated solar flux distribution around the absorber and calculate the optical efficiency. In the present work, three different optical models were studied. Differences of them are summarized in Table 1, and the details of each model are given by Sections 2.1–2.3.

For all the optical models in this paper, some assumptions are made: 1) Do not consider refracting through the glass cover and reflector, and neglect their thickness; 2) Multiple reflections among the absorber, glass tube and reflector are ignored; 3) The reflectivity, transmissivity and absorptivity are independent of incident