

An optimized Monte Carlo ray tracing optical simulation model and its applications to line-focus concentrating solar collectors

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HIGHLIGHTS

- The fluctuation of the MCRT method in the optical simulation was discussed.
- The effects of five main factors on the fluctuation of MCRT were investigated.
- A new MCRT model was proposed to mitigate the fluctuation and reduce runtime.
- The new model was applicable to the optical simulation of various kinds of CSCs.

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ABSTRACT

The Monte Carlo Ray Tracing (MCRT) method has been confirmed flexible and efficient in the optical simulation of Concentrating Solar Collectors (CSCs), but it usually needs higher computing cost and longer runtime or its results fluctuate in multiple runs. The parameters of the way of random number generation, the number of rays, running times, grid numbers, and random number generation times all exerted effects on the simulation results. It was found that running the MCRT model with less number of rays for several more times could mitigate the fluctuation of results and decrease the total runtime simultaneously. Taken the Line-focus CSC with a metal-glass receiver and a parabolic reflector as an example, the maximum (e_{max}) and average (e_{avg}) relative errors of the MCRT method with 1×10^8 rays running for once, 2×10^7 rays running for once and 3×10^6 rays running for five times were all lower than the threshold values ($E_{max} = 5\%$ and $E_{avg} = 0.5\%$), but the total runtime was about 410 s, 82 s and 63 s respectively. On these bases, an optimized MCRT model was proposed by combining the MCRT method with the iteration method, where the minimum running times (t_{min}) and the maximum running times (t_{max}) were introduced, and they could be changed conveniently to meet the requirements of different optical simulations. By applying the proposed model to the Line-focus CSC with a more complex cavity receiver or compound parabolic reflector, the total runtime varied in the range of 268–413 s and 26–102 min respectively, indicating that the runtime reduction was significant when the limit of relative errors were acceptable. The proposed model is beneficial to mitigate the fluctuation, improve the accuracy and reduce the runtime of the MCRT method. It can also be further used to the optical simulation of various kinds of CSCs.

1. Introduction

Efficient use of renewable energy resources exerts a significant role in alleviating the problems of fossil energy shortage and environmental deterioration [1–3]. Among all the renewable energy resources, solar energy has emerged to be one of the most promising resources since it is

abundant, freely available and technically mature in commercial applications [4,5]. To convert low-density solar energy into mechanical energy, Concentrating Solar Collectors (CSCs) and particularly Line-focus CSCs, have been broadly used and investigated [6–9].

The solar flux distribution on the absorber provides accurate boundary conditions for thermodynamic analysis and affects the photo-

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Nomenclature

b	angle between the projection of incident ray on reflector cross section and y axis (rad)
c	angle between incident ray and cross section of reflector (rad)
e_{avg}	average relative errors (%)
E_{avg}	limit of average relative error (%)
e_{max}	maximum relative errors (%)
E_{max}	limit of maximum relative error (%)
f	focal length (m)
I	direct normal irradiance (W/m^2)
L	absorber length (m)
n	number of columns between 0 and 1
N_C	number of control volumes along the circumference of absorber
N_{end}	finalized number of rays
N_i	statistical value of the number of points lying between different intervals
N_L	number of control volumes along the length of absorber
N_{ray}	number of rays
N_{start}	initial number of rays
N_{total}	total number of points generated
q	energy of each photon (W)
Q	energy absorbed by the absorber (W)
t_r	running times
t_{min}	the minimum running times
t_{max}	the maximum running times

W aperture width (m)

Greek symbols

ξ	random number
ρ	reflectance of the reflector
α	absorptance of the absorber
τ	transmittance of the glass cover
η	optical efficiency (%)
τ_r	runtime (s)
ϕ	circle angle of the absorber (deg)
ϕ'	tangential angle of solar disk (rad)
ψ_{rim}	rim angle (deg)
θ	angle between incident ray and y axis (rad)
θ'	deflection angle in the radial direction of solar disk (rad)
ΔN_{ray}	increment of the number of rays

Abbreviations

CPC	compound parabolic concentrator
CPEM	change photon energy method
CSC	concentrating solar collector
LCR	local concentration ratio
MCM	monte carlo method
MCRT	monte carlo ray tracing
PTC	parabolic trough collector
RTM	ray tracing method
RRM	runtime reduction method

thermal performance of collectors [10,11]. The circumferential and axial non-uniform solar flux distribution on the absorber of CSC leads to the non-uniform temperature of the absorber [12] and differential expansion in its different parts [13], which may consequently cause the bending of the absorber tube and the broken of the outer glass cover [14–16].

Up to now, numerous optical models have been proposed to investigate the collector optical performance. Burkhard et al. [17] derived general formulas which specified the heat flux over an arbitrary receiving surface for radiation incident from an arbitrary curved surface. Evans [18] developed an integral relationship for evaluating the intensity distribution on flat absorbers for Parabolic Trough Collectors (PTCs). Jeter [19] constructed the first integral model for evaluating the intensity distribution on both the flat absorber and round absorber tube for PTCs, and later he [20] further developed the model by taking into consideration the non-uniform source and a more practical transmission, reflection and absorption process. With considering the effects of bending, Khanna et al. [21,22] and Khanna and Sharma [23] derived analytical expressions for the concentrated circumferential and axial radiant flux distribution on the absorber tube. The analytical expressions have been verified in Ref. [24] and adopted in Refs. [25–27]. The above-mentioned models required complicated mathematical derivations, and meanwhile the optical and geometrical parameters of collectors could not be changed conveniently. Hence simple and flexible approaches were urgently required in the analysis of the optical performance of collectors with different geometric constructions.

Fortunately, the Monte Carlo Ray Tracing (MCRT) method has been developed as a flexible, rigorous and efficient tool in the optical simulation of CSCs [6,28]. In Refs. [6,28–30], the MCRT model for calculating the concentrated solar flux distribution were developed. While in Refs. [31–35], models for coupled photo-thermal and heat transfer processes of CSCs were developed by combining the MCRT method with the Finite Element Method (FEM) or the Finite Volume Method (FVM). The MCRT method only required a total number of rays for simulation, whereas it usually needed higher computing cost and longer runtime

when there were more ray numbers, or its results fluctuated more violently in multiple runs when there were less ray numbers [36–38]. For example, when the simulated ray numbers increased from 1×10^6 to 9×10^6 , the maximum relative errors between the simulation and reference values decreased from the range of 9.4–13.5% to 3.5–6.1%, and the runtime increased by 9 times (see Ref. [37]).

To tackle these problems, some alternative methods and optimization strategies have been proposed. Song et al. [39] presented a descending dimension algorithm by descending the computational complexity of $O(N^4)$ to $O(N^2)$ in the optical simulation of a PTC system, and its result was in accordance with that of the MCRT method. Nevertheless, this algorithm was only applicable to two-dimensional models as it was based on the symmetrical characteristic of PTCs. Guo et al. [40] introduced a backward Ray Tracing Method (RTM) combined with

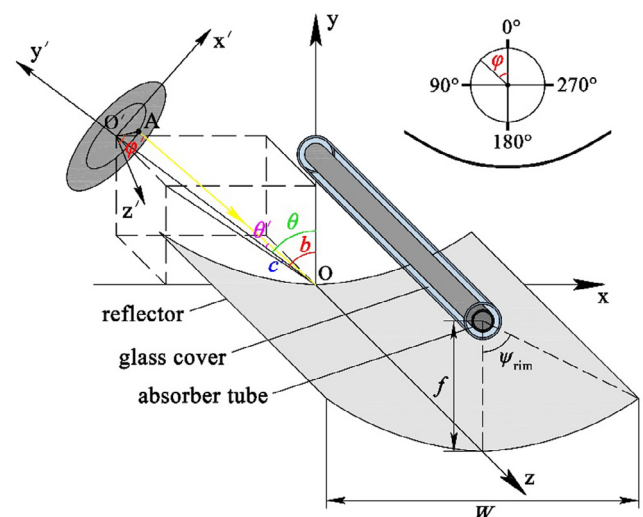


Fig. 1. Schematic of the optical model for a PTC (extracted from Ref. [36]).

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