Applied Energy 201 (2017) 60–68

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A Monte Carlo method and finite volume method coupled optical simulation method for parabolic trough solar collectors

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HIGHLIGHTS

- Four optical models for parabolic trough solar collectors were compared in detail.
- Characteristics of Monte Carlo Method and Finite Volume Method were discussed.
- A novel method was presented combining advantages of different models.
- The method was suited to optical analysis of collectors with different geometries.
- A new kind of cavity receiver was simulated depending on the novel method.

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form 11 March 2017
Accepted 4 May 2017

Keywords:
Parabolic trough solar collector
Monte Carlo method
Finite volume method
Ray tracing
Concentrated heat flux distribution

ABSTRACT

The PTC (parabolic trough solar collector) is widely used for space heating, heat-driven refrigeration, solar power, etc. The concentrated solar radiation is the only energy source for a PTC, thus its optical performance significantly affects the collector efficiency. In this study, four different optical models were constructed, validated and compared in detail. On this basis, a novel coupled method was presented by combining advantages of these models, which was suited to carry out a mass of optical simulations of collectors with different geometrical parameters rapidly and accurately. Based on these simulation results, the optimal configuration of a collector with highest efficiency can be determined. Thus, this method was useful for collector optimization and design. In the four models, MCM (Monte Carlo Method) and FVM (Finite Volume Method) were used to initialize photons distribution, as well as CPEM (Change Photon Energy Method) and MCM were adopted to describe the process of reflecting, transmitting and absorbing. For simulating reflection, transmission and absorption, CPEM was more efficient than MCM, so it was utilized in the coupled method. For photons distribution initialization, FVM saved running time and computation effort, whereas it needed suitable grid configuration. MCM only required a total number of rays for simulation, whereas it needed higher computing cost and its results fluctuated in multiple runs. In the novel coupled method, the grid configuration for FVM was optimized according to the "true values" from MCM of collectors with the maximum geometry difference. Following this, the initialization of photons distribution of collectors with different geometries were conducted with FVM. To demonstrate this coupled model in real practice, performance analysis of a kind of cavity receiver for PTCs was carried out. The judgment of collectors with maximum geometry difference were worth investigating further in the future work.

1. Introduction

The PTC (parabolic trough solar collector) is one of the most promising solar thermal applications, which is widely used for space heating, heat-driven refrigeration, concentrated solar power, etc. The concentrated solar radiation is the only energy source for a PTC, thus its optical performance significantly affects the collector

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http://dx.doi.org/10.1016/j.apenergy.2017.05.047
0306-2619/

Nomenclature

N_1–N_4	number of grids
N_c	number of elements in the circumference of absorber
N_L	number of elements along the length of absorber
e_{max}	maximum relative error (%)
e_{ave}	average relative error (%)
N_{ray}	total number of rays
W_a	reflector aperture (mm)
f	focal length (mm)
d_r	absorber outer diameter (mm)
h_c	cavity depth (mm)
W_c	cavity aperture (mm)
E_{max}	limit of maximum relative error (%)
E_{ave}	limit of average relative error (%)
N_{start}	initial number of rays for MCM
N_{end}	finalized number of rays for MCM
N_{MCM}	the number of times for MCM running
$N_{1.start}$–$N_{4.start}$	initial grids for FVM
Q	absorbed energy by the absorber (W)
I	direct normal irradiance (W/m^2)
A	collector aperture area (m^2)

Greek symbols

ξ_1–ξ_5	random number
ρ	reflectance
τ_r	running time (s)
φ	circle angle of the absorber (deg)
α_c	inclination angle of side absorber of cavity (deg)
α	absorptance
θ	solar angular radius (mrad)
ε	threshold value of photon energy
η_o	optical efficiency (%)
γ	intercept factor

efficiency. Numerous studies have been carried out on optical models to analyze its optical performance, in order to improve the optothermal efficiency.

Jeter [1] constructed a first integral model of the solar flux for PTCs, and in the following year he took into consideration the non-uniform source and a more practical transmission, reflection and absorption in his model [2]. His results have been adopted by many studies e.g. Refs. [3,4]. Khanna et al. [5] derived an analytical expression for the concentrated radiant flux, taking into account circumferential and axial variations as well as the effects of bending. For convenient analysis of the optothermal performance of collectors with different geometric constructions, the combination of the integral or analytical approach with a computer should be conducted in a better way.

Daly [6] presented a backward tracing model to investigate the concentrated flux density by tracing rays backward from the absorber through the reflector to the sun. Chen et al. [7] compressed the solar disk with a diameter parallel to the generatrix of the reflector to establish the optical model, which was verified by the experiment relying on the CCD (charge-coupled device). A descending dimension algorithm for optical simulation of a PTC system was proposed by Song et al. [8], with a computational complexity of $O(N^2)$. The results of this model was in good agreement with that of the MCRT (Monte Carlo Ray Tracing), however the CUP time was shorter. Liang et al. [9] adopted the lumped parameter method to carry out an optical calculation, which was more simple. The models established in [6–9] needed to be extended further for investigating the optical end losses and detailed three-dimensional flux distribution of an actual single-axis tracking PTC system.

Some models can be used for the three-dimensional optothermal simulations. Hachicha et al. [3] developed an optical model based on FVM (Finite Volume Method) and ray trace technology, discretizing a PTC into different grid systems. Cheng et al. [4] derived a modelling algorithm for concentrating solar collectors depending on MCRT. The method was flexible and accessible, adopted by many researches such as Refs. [10–12] to perform the optical or optothermal analysis. Grena [13] established a three-dimensional ray-tracing recursive model to evaluate the optical efficiency and energy distribution of a PTC, taking into account multiple reflections, refractions and various defects. Wang et al. [14] presented a coupled simulation model to simulate the radiation transfer in a solar power system with a cavity receiver, combining the MCRT and Gebhart method. Guo et al. [15] constructed a backward ray tracing model coupled with the lumped effective solar cone. Additionally, some developed softwares were widely used to analyze the optical performance or establish the optothermal models [16–19], e.g. SolTrace, TracePro, ASAP and OptisWorks.

Three optical models based upon MCM (Monte Carlo Method) and FVM have been developed and compared in a previous study by the authors [20], while the comparisons were not comprehensive enough. In this study, a total of four optical models were presented and estimated in detail. On this basis, a coupled optical simulation method was proposed, combining the advantages of both MCM and FVM. This novel method was suitable for carrying out a mass of optical simulations of collectors with different geometrical parameters rapidly and accurately. These simulation results were useful for collector optimization and offered the energy source to the heat transfer model. To demonstrate this method in realistic situations, performance analysis of a kind of cavity receiver for PTCs were carried out.

2. Optical models

In this section, models for simulating the process of both photons distribution initialization and solar radiation reflection, transmission, and absorption are carefully designed on the basis of a previous modeling study by the authors [20]. Four models are proposed and studied to analyze their characteristics. To avoid duplications, only the key information is given below. Taking account of the differences, four different models are presented and summarized in Table 1.

2.1. Photons distribution initialization

As shown in Fig. 1, both FVM and MCM can be used to initialize photons distribution and determine the parametric equations of incident rays.

Table 1
Different optical models adopted in this work.

Models	Photons distribution initialization	Reflection, transmission, and absorption
FM	FVM	MCM
FC	FVM	CPEM
MM	MCM	MCM
MC	MCM	CPEM