Energy Conversion and Management 175 (2018) 278–287

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Geometric optimization of parabolic trough solar collector based on the local concentration ratio using the Monte Carlo method

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ARTICLE INFO

Keywords:
Parabolic trough collector
Collector geometry
Monte Carlo
LCR

ABSTRACT

This research is aimed at geometric analysis of parabolic trough solar collector (PTC) in different sizes of the main components of the system. The rate of the Local Concentration Ratio (LCR) on the receiver tube and optical efficiency are two main features in geometric optimization of the parabolic trough solar collectors. In this work, parabolic trough solar collector was optimized for different sizes with three design variables: the receiver diameter, the collector aperture width and the rim angle. The method used in this research was the Monte Carlo Method (MCM) in MATLAB. The optical and geometric modeling was developed for coding in MATLAB. For the case study, a parabolic trough solar collector was used in the laboratory. The current results showed that the optical efficiency of 65% was obtained for the collector components with the collector aperture width of 0.6 m, rim angle of 100° and receiver diameter of 0.025 m. Also, the optical efficiency of 61% was obtained for the collector with the aperture width of 0.7 m, rim angle of 90°, and diameter receiver of 0.025 m.

1. Introduction

Over the past decade, a large number of research works has been dedicated to analyzing and discussing various aspects, types and applications of solar energy systems [1]. Among all the solar thermal technologies, the parabolic trough solar collector (PTC) is technologically and commercially important [2]. One of the key parameters for increasing the solar energy conversion is increasing the efficiency of the parabolic trough solar collector by optimizing the collector geometry, changing the working fluid, and selecting appropriate materials for the absorber tube [3]. By determining the geometry and thermal efficiency of a PTC system, the thermal performance and the heat transfer fluid (HTF) energy can be estimated at different conditions. A PTC system usually works up to 400° C [4]. One of the most important and key elements in this system is the ratio of the concentration of solar radiation (concentration rate) to the receiver surface area [5]. Monte Carlo Ray Tracing (MCRT) simulation is a randomized simulation method based on probable data which is used for accuracy and ability to solve various problems, such as solar power concentration research works [6]. Many studies have been carried out on the optical performance, thermal performance, and optimization of parabolic trough collectors. Optical simulation for PTC was carried out by Grena [7]. Bin Yang et al. [8] has presented a paper called calculation of the Concentrated Flux Density Distribution for parabolic solar collector using Monte Carlo. They examined the geometric concentration ratio and rim angle. This three-dimensional simulation was focused on the total optical efficiency, the absorbed radiation distributions on the surface of the receiver, and the energy absorbed by the glass cover. For improving the thermal performance of PTC, the combination of two methods of Finite Volume Method (FVM) and MCRT was presented by He et al. [9]. They initially used the MCRT method to determine the distribution of thermal flux, and then, they used the FVM method to improve the thermal performance.

In 2012, Cheng et al. [10] performed a numerical simulation for a PTC, using the combination of the two methods of FVM and MCRT. They used four types of gas and four types of oil as the working fluids in their study. Designing the PTC system with Microsoft Visual Studio software was performed by Woldmichael et al. [11]. They used empirical data to validate their results. Yousuf Alaydi [12] proposed a model for desalination using a PTC system, instead of using fossil fuels. A new model of the MCRT method, applicable for concentrated solar collectors, was presented by Cheng et al. [13]. They used PTC, PDC and PVR collectors in their study. Cheng et al. [14] performed a comparison and sensitivity analysis for different modes of PTC components, using the Monte Carlo method. Balghouthi et al. [15] conducted a study to evaluate the optical and thermal properties of a PTC used for a cooling

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https://doi.org/10.1016/j.enconman.2018.09.001
Received 3 April 2018; Received in revised form 23 August 2018; Accepted 1 September 2018

Nomenclature

A_a	aperture area (m^2)
A_f	parabolic geometry factor
A_l	shadow surface area on the reflector (m^2)
A_r	receiver area (m^2)
Cr	concentration ratio
D	receiver diameter (m)
d^*	universal nonrandom error parameter due to dislocation
f	focal distance (m)
hp	parabolic vertical height (m)
I_b	solar intensity (W/m^2)
Q_S	heat flux (W/m^2)
r_r	rim radius (m
TR	receiver temperature (K)
W_a	collector aperture (m)
R	vector of incoming rays

Greek symbols

ρ	vector of reflected rays
ψ	angular coordinate (degree)
θ_i	incidence angle (degree)
θ_m	half acceptance angle (degree)
α	absorptance
τ	transmittance
φ_r	collector rim angle (degree)
γ	intercept factor
η_{MCM}	optical efficiency (MCM)
η_o	optical efficiency
Φ	angle between focus axis and reflector surface (degree)
σ^*	universal random error parameter
β^*	universal nonrandom error parameter due to angular errors

Abbreviations

FVM	Finite Volume Method
HTF	Heat Transfer Fluid
IMCRT	Inverse Monte Carlo Ray Tracing
LCR	Local Concentration Ratio
LFR	Linear Fresnel Reflector
MCM	Monte Carlo Method
MCRT	Monte Carlo Ray Tracing
PTC	Parabolic Trough Solar Collector

Subscripts

a	absorber
b	beam radiation
F	factor
L	loss
i	incidence
o	optical
r	receiver

system. They used photogrammetric techniques for optical evaluations. It is also used with the MATLAB code for optical analysis. In 2014, Akbarimoosavi et al. [16] studied the 3D Thermal-structural analysis of an absorber tube caused by a 3D solar flux density distribution. They used the Monte Carlo method to determine the LCR and distribution of heat flux. The results were specified for the ratio of local concentration, flux density, temperature distribution and thermal expansion for the designed conditions. Experimental and numerical heat transfer analysis of a V-cavity absorber for a linear parabolic solar collector carried out by X.Xiao et al [17]. They used the MCRT method to examine the optical performance.

Mwesigye A et al. [18] studied the thermal and thermodynamic analysis of parabolic trough receiver at different concentration ratio and rim angles. They used MCRT method to measure thermal flux on receiver and the computational fluids dynamic method to determine the thermal and thermodynamic performance. Design and numerical study for a new type parabolic through solar collector with uniform solar flux distribution carried out by Wang Kun et al. [19]. They obtained the concentrated solar flux distribution using Monte Carlo Ray Tracing method. In the same year, Valenzuela et al. [20] examined the large-size parabolic trough solar collectors, empirically. In this study, a large size PTC system (length of 100 m) was used to evaluate its optical and thermal performance. The development of empirical equations for the radiation profile of a standard PTC system (LS2), by the Monte Carlo method, was studied by Islam et al. [21]. They developed geometric optimization equations based on the LCR and optical efficiency for both the glass and non-glass receivers. In 2015, Desai et al. [22] optimized a solar power plant with a PTC system. In their study, they examined the energy and assessed the economy of the power plant. The S-curve absorber tube design for a PTC system was investigated by Demagh et al. [23]. They used the Monte Carlo method to obtain the heat flux distribution on the receiver surface. In 2015, Qiu et al. [24] examined the optical and thermal performance of a Linear Fresnel Reflector (LFR) system by the hybrid approach of FVM and MCRT. The method, used in this study, was the Monte Carlo method, and the results were compared with the Tracepro and Soltrace software. They achieved the optical efficiency of 65%, and thermal efficiency of 46%. In 2015, Fuqiang et al. [25] examined the effects of the glass tube shape on the distribution of heat flux on the receiver. They used a circular-oval combination for the glass tube cross-section.

In 2016, J. J. Serrano-Aguilera et al. [26] used the Inverse Monte Carlo Ray Tracing (IMCR) for linear collectors. They used this method for geometric design of reflector to achieve a reasonable distribution on absorber tube. Cuizhen Zhang et al. [27] analyzed the optical sensitivity of geometry deformation of parabolic solar collector using Monte Carlo method. In this study, they examined the effect of three type of deformation including global deformation, local rotation deformation and local linear deformation. Aggrey Mwesigye et al. [28] analyzed the thermal performance and enthalpy production for a parabolic solar collector with high concentration ratio using Cu-Thermioal VP-1 nano fluid. They used the Monte Carlo method to provide the thermal flow on an absorb receiver tube then they combined it with finite volume method to measure the thermodynamic performance. In 2017, Bin Zou et al. [29] conducted a detailed study on optical performance of parabolic solar collector using MCRT method based on theoretical analysis. They used sensitivity analysis of different parameters. Majedul Islam et al. [30] studied the physical and optical effects on optical performance of the parabolic solar collector. They examined three fundamental parameters including LCR, optical efficiency and mean light concentration using Monte Carlo method. In 2018, Omid K. Sadeghiyani et al. [31] studied the energy and exergy analysis of a LS-2 parabolic solar collector. The measured the thermal flux on the receiver using Monte Carlo method. In the same year, Man Fan et al. [32] presented an optical simulation model for linear solar concentrators by MCRT method. Their purpose was to improve accuracy and reduce runtime.

Although some research works have been conducted on the optical performance of different PTC systems, it is rarely possible to find a study on the effects of geometric changes in the components of the PTC system on optical efficiency. The nanofluid thermal performance in a