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A detailed study on the optical performance of parabolic trough solar collectors with Monte Carlo Ray Tracing method based on theoretical analysis

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ABSTRACT

The optical performance of a parabolic trough solar collector (PTC) is studied comprehensively based on Monte Carlo Ray Tracing method (MCRT) and theoretical analysis. The MCRT models are established, and the theoretical equations of several critical parameters are derived firstly. And then the effects of different geometrical parameters on the optical performance are discussed in detail. It is revealed that the distribution of local concentration ratio around the absorber tube changes greatly, and cannot be divided into four parts as previous studies showed for some special parameter conditions. The theoretically derived parameters explain very well the different properties for the critical conditions. The variations of those parameters with different geometrical configurations are further displayed. Accordingly, the optical properties for different critical parameters are discussed. The size relationship between the reflected light cone and the absorber diameter affects the optical efficiency significantly because of the rays escaping effect. Practically, the absorber diameter should be larger than the size of the reflected light cone to avoid great optical loss caused by rays escaping. All the findings in this paper establish the foundation for further research on the optical-to-thermal energy conversion in the PTC system, and provide a reference for designing and optimizing PTC's structure.

1. Introduction

Energy shortage and environmental deterioration, caused by excessively consuming fossil fuels, have become severe issues facing humans over past decades (Geyer, 2007; Kalogirou, 2004; Tian and Zhao, 2013). A promising solution is to exploit and utilize renewable energy resources as the alternatives to fossil fuels, which has attracted extensive attentions (Geyer, 2007; Vijay et al., 2013). As the most widely distributed renewable energy resource, solar energy has been applied in various social industries (Fernandez et al., 2010; Kalogirou, 2004). The parabolic trough solar collector (PTC) technology used in solar power system is the most cost-effective technology for utilization of solar energy (Jebasingh and Joselin-Herbert, 2016; Price et al., 2002). As the most important component, solar collectors have significant effects on the cost and performance of the whole system (Schiel, 2012). Thus, to reduce the cost and enhance the competitiveness of solar power technology to traditional fossil power plants, further improvements of the solar collector is essential.

A parabolic trough solar collector (PTC) focuses the reflected solar rays from the parabolic reflector onto the receiver tube that is located at the focal line. And then the reflected solar radiation is absorbed and converted to thermal energy, and transferred to the heat transfer fluid (HTF) flowing in the absorber tube. The process of the photo-thermal conversion is complex, and the distribution of the solar energy flux on the absorber is the boundary condition for heat transfer calculation (Cheng et al., 2010; Hachicha et al., 2013; He et al., 2011, 2012). Therefore, the optical performance has great effects on the overall performance of the PTC. During 1970s and 1980s, the simplified geometric analysis method was the most widely used method for studying PTCs' optical performance, and some basic properties have been found (Burkhard et al., 1973; Evans, 1977; Nicolas and Duran, 1980; Duran and Nicolas, 1984; Riveros and Oliva, 1986). Later, the integral methods were adopted to improve the results' accuracy (Huang et al., 2012; Jeter, 1986a, 1986b). Buie et al. (2003a, 2003b) developed a calculation model of the sunshape, which was usually used to simulate the real energy intensity distribution of the solar disk in other references. Ray Tracing Method (RTM) was another effective method to be used for optical performance study. Daly (1979) proposed a backward ray tracing method to

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Nomenclature

A_i	area of the *i*th grid (m^2)
CL	local concentration ratio
CL_i	local concentration ratio of the *i*th grid
CL_{max}	maximum local concentration ratio
CL_{ave}	average local concentration ratio
d_a	absorber tube out diameter (m)
$d_{a,re}$	required diameter of the absorber tube to avoid rays escaping (m)
d_g	glass envelope out diameter (m)
f	focal length (m)
I_D	direct normal solar radiation intensity (W/m^2)
I_{eff}	effective solar radiation intensity incident on the aperture (W/m^2)
I_i	local energy flux density of the *i*th grid (W/m^2)
L_a	absorber tube length (m)
N_c	grid number in the circular direction of the absorber
N_z	grid number in the length direction of the absorber
N_n	total number of grids
N_{ray}	total number of rays
W	aperture width (m)

Greek symbols

α_a	absorptivity of the absorber
χ	angle span at the bottom of the absorber without receiving any reflected rays (°)
δ	radial angle of the sun (δ = 4.65 mrad)
ε	nonuniformity of solar flux density distribution on the absorber tube
ϕ	angle for auxiliary calculation (°)
γ	intercept factor
η_o	optical efficiency (%)
φ_a	circumferential angle of the absorber (°)
φ_s	circumferential angle of the point on the solar disk (mrad)
θ_s	radial angle of the point on the solar disk (mrad)
ρ_r	reflectivity of the parabolic reflector
τ_g	transmissivity of the glass envelope
Ω	effective angle span receiving concentrated beam (°)
ψ	position angle of the point on the parabolic reflector (°)
ψ_{rim}	rim angle (°)
$\kappa_1 \sim \kappa_8$	uniformly distributed random number between 0 and 1

Abbreviations

FVM	Finite Volume Method
HTF	heat transfer fluid
MCM	Monte Carlo Method
MCRT	Monte Carlo Ray Tracing
PTC	parabolic trough solar collector
RTM	Ray Tracing Method

study the energy flux distributions of cylindrical concentrators. However, the method was just for two-dimensional analysis. Grena (2010) developed a three-dimensional model based on the ray tracing recursive algorithm. In the following paper (Grena, 2011), he further discussed the efficiency gain of a PTC with an infrared-reflective film on the non-radiation part of the receiver. Jiang et al. (2010) established an optical model for two-stage PTCs using the spectral beam splitting method, which took into account the optical cone and the absorber diameter for the incident angle of 0°. Khanna et al. (2013, 2015) developed analytical expressions for both the circumferential and axial flux distribution on a bent absorber tube. Their optical models were relatively practical, and were verified by the following experimental results (Khanna et al., 2016).

In recent years, the Monte Carlo Ray Tracing (MCRT) method has been widely adopted to simulate the optical characteristics of concentrating solar collectors for its high efficiency and flexibility (Shuai et al., 2008; Wang et al., 2012, 2013; Yang et al., 2010). Cheng et al. (2013) developed a novel unified MCRT code for simulating typical concentrating solar collectors. In the later papers (Cheng et al., 2014a, 2014b), they investigated the concentrating characteristics of different PTCs based on MCRT. Many other researchers (Cheng et al., 2012; Hachicha et al., 2013; He et al., 2011; Wu et al., 2014) combined the MCRT with the Finite Volume Method (FVM) to study the photo-thermal conversion process of the PTC system.

Although many researches on the optical performance of the PTC were conducted, seldom has literature been found which thoroughly discussed the effects of geometrical configuration on concentrating characteristics. In Refs. Cheng et al. (2014a, 2014b), only the sudden drop of the optical efficiency caused by rays escaping effect was theoretically explained. It did not give clear explanations of changes in some critical conditions, and never discussed the effects of these parameters on optical properties. In this paper, the flux distribution characteristics on the absorber of a PTC were investigated in detail based on MCRT. And the effects of different geometrical parameters on the optical efficiency were further studied. Equations of several critical parameters were derived theoretically, and the variations of these parameters with different geometrical configurations were further displayed. Accordingly, the optical properties for different critical parameters were discussed. It was also proved that all the simulation results could be well explained by the theoretical analysis results.

2. Model and methodology description

2.1. Physical model

The schematic diagram of a parabolic trough solar collector (PTC) is shown in Fig. 1(a). From the figure, it can be seen that a PTC module is mainly composed of a parabolic trough reflector and a receiver tube. Many important geometrical parameters are displayed in the figure, such as the aperture width (W), the focal length (f), the absorber tube outer diameter (d_a), the glass envelope diameter (d_g), the rim angle (ψ_{rim}), and the radial angle of the sun (δ signifies the finite size of the solar disk). The Cartesian coordinate system OXYZ used here is also established. The origin of coordinates (O) is the apex of parabola, X-Y plane contains the cross section of the parabolic trough, with Y axis passing through the vertex and the focus, and Z axis is through the vertex and parallel to the focal line. As is shown in Fig. 1(b), the receiver tube consists of a metal absorber tube with selective absorbing coatings on its outer surface and a glass envelope. The annulus between the metal absorber and glass envelope is kept vacuum to reduce heat loss and protect the coatings from oxidation. Metal bellows are used as the metal-glass joints to compensate the expansion difference between the metal and glass. Some other parts, such as getters and evacuation nozzle may also be used to maintain the vacuum state in the annulus.