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Modeling and simulation of ray tracing for compound parabolic thermal solar collector

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ABSTRACT

A ray tracing model for the compound parabolic collector (CPC) is presented in this work. The pertinent parameters for the compound parabolic thermal solar collector are analyzed and calculated, and the ray tracing model is further investigated. The ray tracing model is validated by comparing our ray tracing model results with a commercial optical software. Each ray is traced by the CPC model, so the incident angle is calculated when solar ray enters the absorption tube. The ray tracing model was applied to the thermal efficiency analysis of the CPC, and the thermal performance results obtained by the model and test results were compared.

1. Introduction

Due to the rapid consumption of fossil fuels in the world, it is necessary to find alternative energy sources to meet current daily needs. At the same time, people are increasingly interested in concentrating solar thermal systems as an alternative and/or supplement to existing fossil fuels or nuclear fuel generation systems [1–2]. Solar concentrating technology aims to concentrate the direct normal insolation (DNI) in solar energy, to convert it directly and efficiently into thermal energy. Low-cost concentrator technologies are important research topics [3]. Compound parabolic concentrator (CPC) is a non-imaging low-focus concentrator, designed according to the principle of optics. The receiver can collect the sunlight in a certain range of the incident angle of the incident ray so that it can receive both DNI and diffuse radiation.

Aiming at the tubular CPC, the ray tracing software TracePro was used to analyze the CPC and the optimization scheme was proposed according to the simulation results. The CPC collectors with the concentration ratio of three and six were tested, and the heat loss and thermal efficiency of the thermal properties, used in such as industrial processes and solar refrigeration were investigated. The CPC collectors are desirable and reachable within the temperature range of 80 to 250 °C, as they do partly collect diffuse radiation and can avoid the high cost of accurate tracking system [4]. Buttinger et al. [5] demonstrated a new, flat, non-tracking V-type collector with a concentration ratio of 1.8. The prototype of this collector shows an efficiency of about 50% under the irradiation intensity of 1000 W/m^2 and 150 °C, collector temperature. Harmim et al. [6] developed a novel box-shaped CPC solar cooker with asymmetry and analyzed its thermal properties using a detailed theoretical model.

Baig et al. [7] worked out a CPC with a geometric concentration ratio of 7.5 and their experiment showed that the peak efficiency could exceed 45% when using a vacuum tube receiver. The general solar water heater system can meet the demand of low temperature hot water, but it is less efficient when it is more than 55°. Pei et al. [8] built a CPC hot water system test setup and investigated its high water temperature performance. Their experiments show that winter thermal efficiency is more than 43%. Using U-tube solar energy set for the water heater system, the higher water temperature results in a much better thermal performance. Tang et al. [9] analyzed the amount of annual radiation that CPC, which is mounted on the stand oriented E-W in China can receive.

The solar absorption ratio of absorber tube depends on the incident angle when solar ray enters the absorption tube, and the commercial optical software cannot account for the absorption ratio with the incident angle changes. As such the commercial software can not accurately carry out the simulation. In this work, the ray tracing model is used to simulate the process of concentrating sunlight, the number of reflections of the sunlight and the incident angle of the sunlight when it enters the absorber tube. The CPC concentrating sunlight process is programmed according to the established model while addressing applications.

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Nomenclature

A_s	overflowing area (m^2)
$A_{Aperture}$	CPC aperture area (m^2)
c_r	concentration ratio
r	absorber diameter (m)
I_b	solar beam radiation intensity (W/m^2)
I_d	diffuse radiation intensity (W/m^2)
k	slope

Greek symbols

α	absorption ratio
θ_0	the angle between ray and the surface of the absorbing coating (°)
θ_1	half-acceptance angle (°)
θ_t	transversal projection angle (°)
θ_l	longitudinal projection angle (°)
η_o	thermal efficiency of the absorber tube
η_{ob}	DNI optical efficiency
η_{od}	diffuse optical efficiency
ξ_b	DNI geometric optical efficiency
ξ_d	diffuse geometric optical efficiency
ρ_b	reflectivity of DNI
ρ_d	reflectivity of diffuse radiation
α_b	DNI absorption ratio
α_d	diffuse absorption ratio

Abbreviations

CPC	compound parabolic collector
DNI	direct normal insolation

2. Model description

2.1. Physical model

The solar collector section is composed of parabolas and involutes, which are shown in Fig. 1. This CPC has a half-acceptance angle of θ_1. The right parabola has an entrance aperture of DC and a focal point F_1. The Ray tracing process for CPC in collecting solar energy will be analyzed based on the assumption that the direction of sunlight passing through the glass envelope does not change.

2.2. Mathematical model

For the CPC curve with Cartesian coordinates, expressions can be deduced from analytical geometry, accounting for the fact that the symmetry axis of the parabolas is tangent to the absorber. $T(x,y)$ is a point on the parabolas and point O is the Cartesian plane origin. The coordinates of a point on the involutes are given by the following parametric equations:

$$\begin{cases} x = r(\sin\theta - \theta\cos\theta) \\ y = -r(\cos\theta + \theta\sin\theta) \end{cases} \tag{1}$$

The coordinates of the point $T(x,y)$ on the parabolas are expressed by the following parametric equations:

$$x_T = \frac{r}{1-\cos\theta_R}[\cos\theta_1(1-\cos\theta_R) + (\pi + 2\theta_1)\sin(\theta_R - \theta_1)] \tag{2}$$

$$y_T = \frac{r}{1-\cos\theta_R}[\sin\theta_1(1-\cos\theta_R) + (\pi + 2\theta_1)\cos(\theta_R - \theta_1)] \tag{3}$$

where θ_R is the angle between the line from point $T(x,y)$ to the parabolic focus F_1 and the right parabolic symmetry axis. According to the involute equation, the parametric equation of the involute tangent slope in Cartesian coordinate system is obtained as:

$$k_1 = \frac{dy}{dx} = \frac{dy/d\theta}{dx/d\theta} = \frac{-r\theta\cos\theta}{r\theta\sin\theta} = -\frac{1}{\tan\theta} \tag{4}$$

The parametric equation of the involute normal slope k_{1n} in the Cartesian coordinate system is calculated as:

$$k_{1n} = -1/k_1 = \tan\theta \tag{5}$$

The parametric equation of the parabola's tangent slope k_2 is represented as:

$$k_2 = \frac{dy_T}{dx_T} = \frac{dy_T/d\theta_R}{dx_T/d\theta_R} \tag{6}$$

where the numerator and denominator are derived as follows:

$$\frac{dy_T}{d\theta_R} = \frac{r}{(1-\cos\theta_R)^2}\{(1-\cos\theta_R)[\sin\theta_1\sin\theta_R - (\pi + 2\theta_a)\sin(\theta_R - \theta_1)] - \sin\theta_R[\sin\theta_1(1-\cos\theta_R) + (\pi + 2\theta_1)\cos(\theta_R - \theta_1)]\} \tag{7}$$

$$\frac{dx_T}{d\theta_R} = \frac{r}{(1-\cos\theta_R)^2}\{(1-\cos\theta_R)[\cos\theta_a\sin\theta_R + (\pi + 2\theta_a)\cos(\theta_R - \theta_a)] - \sin\theta_R[\cos\theta_a(1-\cos\theta_R) + (\pi + 2\theta_a)\sin(\theta_R - \theta_a)]\} \tag{8}$$

The parametric equation of the parabola's normal slope k_{2n} is obtained as:

$$k_{2n} = -1/k_2 \tag{9}$$

Based on Eqs. (1)–(9), the reflected light can be obtained from the incident light using the reflection law. Fig. 2 shows the programming flowchart for CPC ray tracing.

2.3. Model validation

In order to verify the accuracy of the ray tracing model, the tracing result was compared with the results obtained by the commercial optical software TracePro.

The characteristics of the CPC are listed in Table 1. The black curves in Fig. 3 represent the CPC, the circle in the middle of Fig. 3 is the collector, and blue lines are the traced rays.

Transversal projection angle θ_t is defined as the angle between the collector normal vector (n_c) and the sun position vector (SOL) projected

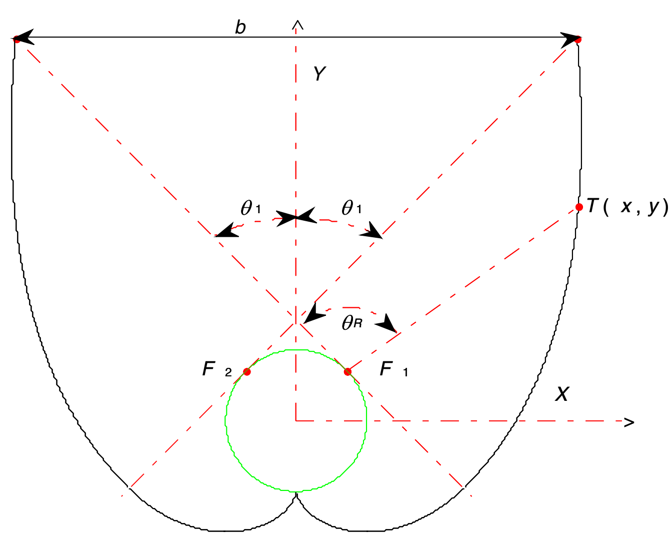

Fig. 1. Basic schematic of CPC.