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An algorithm for the flux distribution over the flat absorber of a parabolic trough concentrator

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Abstract

Based on the symmetries of the parabolic trough concentrating system and the solar radiation, a descending dimension algorithm has been developed with a computational complexity of $O(N^2)$, whereas that of the Monte Carlo ray tracing (MCRT) method and the finite element method are of $O(N^4)$ The formula of the energy function $\psi(\theta)$ for solar disk slice was constructed to solve the integration of the flux distribution. The numerical results indicated that the results obtained by the presented algorithm have a good agreement with results produced by MCRT, meanwhile CPU time requirement of the algorithm is about a few seconds, much shorter than that of MCRT. The formulas for calculating the number of reflections of ray tracing within a homogenizer and the exact coordinates of the landing location on the absorber of each ray are established from geometrical aspect. The effect of the homogenizer for flux density uniform is clearly characterized.

Keywords: Parabolic; Flux distribution; Concentration; Flat absorber

1. Introduction

Parabolic trough concentrator with a flat absorber is an important type of line focus parabolic system in solar energy field, and this kind structure is universally adopted by the concentrated photovoltaic thermal system (CPVT) (Baig et al., 2013; Karathanassis et al., 2013). Numerous reviews on CPVT heat conduction and dissipation can be found in the literature: studies have shown that the solar irradiation intensity distribution over a flat absorber is not uniform and reaches the peak at the center portion (Baig et al., 2013), which produces a hot spot effect. This non-uniform flux density distribution leads to a non-uniform temperature profile over the absorber. This temperature gradient results in different degrees of expansion of different parts of the absorber. Accordingly, such huge non-uniformity in the flux density distribution will make stress distribution over the absorber exceed an allowable value. Thus, in order to optimize the absorber design regarding heat conduction and dissipation, the flux density distribution over a flat absorber must be calculated. The flux density distribution over a flat absorber can be used to optimize the design of the heat sink module of the CPVT systems. Because only a small portion of the concentrated irradiation can be converted into electrical power and most of the radiation energy is transformed into heat. A heat sink with an optimization design can dissipate heat quickly to prevent high temperatures that can damage the photovoltaic components (Sharaf and Orhan, 2014).

The flux density distribution over an absorber depends on many factors, such as sunshape, rim angle, incident

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Nomenclature

W	aperture of parabolic mirror (m)
V	length of parabolic mirror (m)
f	focus length of parabolic mirror (m)
M	half-width of flat absorber (m)
R	incident ray light cone
H	height of homogenizer (m)
α	the angle between the incident ray from the central solar disk and the cross section of the trough, perpendicular to its focal line (degree)
e_x	tube alignment error on X-axis (m)
e_y	tube alignment error on Y-axis (m)
e_t	sun tracking error (mrad)
δ	radial angular bounds of the solar disk, 4.65 mrad
φ	circumferential direction (degree)
β	angle between L_1 and L_2 (mrad)
σ	angle between the absorber surface and the reflect ray on the edge of the trough (degree)
N	number of sample points on a direction
GC	geometric concentration ratio, $GC = W/2M$
n	opening ratio, $n = W/f$
E	energy (J)
ϕ	function for Buie sunshape
ψ	function for the slice sunshape
θ	radial angular displacement (mrad)
χ	circumsolar ratio
Σ	total power accepted by the absorber (W)
NR	number of reflections

Subscripts

W	width direction of parabolic mirror
V	length direction of parabolic mirror
SD	solar disk
Δ	radial angular bounds of the circumsolar regions (mrad)

angle, tracking error and alignment errors. Rabl (1976) has studied the geometric concentration ratio of different types of concentrators and indicated that there is a nonuniformity of the flux density distribution on the absorber. Evans (1977) used an optical cone method to evaluate the solar flux density distribution for the specific case of $\alpha = 0$. Jeter (1986, 1987) and Nicolás and Durán (1980) further developed this approach to derive the flux density distribution formulas for a trough-type with a flat absorber. The actual non-uniform brightness profile on the solar disk is known as the sunshape. But in early studies in the literature, a uniform profile or a Gaussian profile is used. The difference between these two types of profiles and the actual sunshape leads to an error in the calculated results. Although these analytic approaches are defined clearly and mathematically, those formulas are sophisticated and inconvenient to use them in engineering analysis and design.

The Monte Carlo ray-tracing method (MCRT) was created with the advances in computer technology. The MCRT directly utilizes the powerful computational capability of computers to create a large amount of stochastically created ray tracing over the surface, for example billions of light ray, to simulate the flux density distribution over the absorber. The MCRT possesses the flexibility to handle a complex optical model. Similar to MCRT, the finite element method is another computer method to simulate the flux density distribution. The difference is that finite element method uses regular ray instead of stochastically created ray tracing. However, both MCRT and the finite element method have the disadvantage of requiring long CPU time, about hours. In the view of mathematic, the MCRT and the finite element method use quadruple integration, which means a computational complexity of $O(N^4)$ and would result in long CPU time (He et al., 2011; Jiang et al., 2010).

Based on the formulas that were derived by Evans (1977) and Jeter (1986, 1987), by fully excavating the cylindrical symmetry of the parabolic trough concentrator and the radial symmetry of the sun brightness function, a descending dimension algorithm for mapping the flux density distribution on a flat absorber of a parabolic trough was developed. This algorithm has a computational complexity of $O(N^2)$ compared with $O(N^4)$ for the MCRT and the finite element method. Thus, the developed algorithm will reduce the required computation by 3 to 4 orders of magnitude (for $N \approx 100$), and the entire computation process can be completed in seconds. In the developed algorithm, the sunshape formulated by Buie et al. (2003) was adopted, which is based on the temporal observation data and is more accurate than a uniform or the Gaussian profile. The developed algorithm can be easily used to analyze the situation with existing tracking and alignment errors.

The rest of this paper is organized as follows. First, the principles of the dimension reduction algorithm and the computational procedure are introduced. Then, the calculation results of the developed algorithm are compared to those in the classical literature and that based on MCRT. In Section 4, the flux density distribution for various parameters of the concentrator under undesirable conditions is presented. In Section 5, a homogenizer is introduced to maintain a uniform flux density distribution on the flat absorber. The formulas for calculating the number