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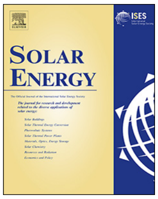

# A tool for fast flux distribution calculation of parabolic trough solar concentrators

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ABSTRACT

Parabolic trough concentration (PTC) systems are widespread technologies for the large-scale exploitation of solar energy. The flux density on the wall of the absorber of a PTC is non-uniform and complicated, and the calculation of flux distribution is key for estimating the optic performance of a PTC and analyzing the flow characteristic of the fluids in the tubular absorber. Traditional 3D ray-tracing methods for the calculation of flux distribution consume many computational resources and involve long CPU running time. This paper presents a 2D method for the fast calculation of the flux distribution of a PTC based on a descending dimension algorithm. By converting the PTC optical model from 3D space to 2D space, the calculation consumption required by the presented 2D method shrinks by two orders of magnitude compared to traditional 3D ray-tracing methods. Upon assessment, the method demonstrates a capacity to work out the flux density distribution within 0.22 s, compared to approximately 40 s required by traditional 3D ray-tracing methods, using a standard personal computer with a level of good accuracy, with a standard deviation of approximately 0.3 suns. Mathematical proof of this method was also provided. The numerical results were compared with those from the literature and a good agreement was observed, with the average standard deviation of 0.359 suns under different incident angles, proving the reliability of the method presented here. Based on this 2D method, a software tool was developed to facilitate the analysis of characteristics of solar PTC systems.

## 1. Introduction

Concentrated solar thermal power is increasingly being considered as a potential solution for the industrial-scale exploitation of solar energy (Kalogirou, 2004; Kuravi et al., 2013; Tian and Zhao, 2013). Due to the geometric structure of PTC and other optical factors, the flux density distribution of the tubular absorber is not uniform. Consequently, local overheating and complicated flow field of the transfer medium in the tubular absorber can occur. Therefore, the calculation of flux distribution is important and valuable in engineering. Therefore, irradiation flux distribution has recently become a popular topic attracting greater attention.

The direct measurement of concentrated high flux distribution is difficult to conduct online because of the rigorous conditions of engineering and space limitations. In practice, researchers usually adopt analytical or numerical methods to calculate flux distribution (Eck et al., 2004; Hachicha et al., 2013; Kalogirou, 2004; Roldán et al., 2013; Song et al., 2014; Wang et al., 2010; Wirz et al., 2012; Yang et al., 2012). Jeter developed a semi-analytic method to calculate the flux distribution on the tubular absorber of a PTC under ideal conditions (Jeter, 1986, 1987). Khanna et al. proposed an analytical expression of flux distribution under alignment error along the y axis (Khanna et al., 2013). However, in actual engineering, there are many non-ideal various conditions, such as tracking errors, non-orthogonal incident rays, and transcendental sunshape profiles (Coventry and Blakers, 2006; Lüpfert et al., 2005; Pottler et al., 2005; Pottler et al., 2014; Riffelmann et al., 2006; Xiao et al., 2012), which have significant influence on the optical efficiency of PTC and are difficult to manage using analytic methods (Cheng et al., 2014).

Considering various complex conditions, ray-tracing methods have been developed in recent years that use billions of rays to simulate the concentration process. The advantage of ray-tracing methods its flexibility for calculation of flux distribution of PTC under various conditions. According to the rays' simulating strategies, ray-tracing methods are usually grouped into two types, the finite element ray-tracing method (FEM) (Grena, 2010; Hachicha et al., 2013; Jiang et al., 2010)

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## Nomenclature

| | |
|---|---|
| $D_{rk}$ | internal bisector |
| $E_{P_{r0}}$ | energy of $P_{r0}$ from Π |
| $e_{P_{r0}}$ | energy of $P_{r0}$ from a reflection band, suns |
| $e_{sd}$ | relative error of a single band, dimensionless |
| $f$ | focal length of parabolic mirror, m |
| i, j, k | unit vector |
| $L$ | length of parabolic mirror, m |
| $l_0$ | ideal axial line of the reflected ray cone |
| $l_0'$ | ideal projection of axial line of the reflected ray cone |
| $l_1$ | actual axial line |
| $l_1'$ | projection of actual axial line |
| $l_{r1}$, $l_{r2}$ | direction vector of receiving bands |
| $N$ | grids along the dimension |
| $n_i$ | order number of samples |
| $l_\theta$ | distance from center to subtense on auxiliary sundisk, m |
| $n_{sd}$ | number of slice on sundisk |
| $n_{tr}$ | number of slice on trough |
| $P$ | geometrical point |
| $P_{r0}$ | researched point on receiver |
| $R$ | radius of receiver tube, m |
| $R_{sd}$ | radius of auxiliary sundisk, m |
| $t$ | band direction vector |
| $t_1$, $t_2$ | direction vector of the flux band on the sundisk |
| $t_{10}$, $t_{20}$ | unit direction vector of the flux band on the sundisk |
| $W$ | aperture of parabolic mirror, m |
| $u$ | auxiliary variable, dimensionless |
| $x$, $y$, $z$ | Cartesian coordinates |

*Greek letters*

| | |
|---|---|
| $\alpha$ | incident angle, degree |
| $\beta$ | angle variable, degree |
| $\gamma_s$ | radial angular displacement of sundisk, mrad |
| $\Delta_s$ | Gaussian slope error, degree |
| $\Delta_t$ | sun tracking error, mrad |
| $\Delta_y$ | tube alignment error on the X axis, m |
| $\Delta_y$ | tube alignment error on the Y axis, m |
| $\Delta\theta$ | the angle between plane $\Omega_1$ and $\Omega_2$, rad |
| $\Delta\theta_c$ | difference of two adjacent spots |
| $\delta$ | solar half-angle, 4.65 mrad |
| $\varepsilon_{sd}$ | relative error from slice direction on sundisk, dimensionless |
| $\varepsilon_{sy}$ | relative error of system, dimensionless |
| $\theta$ | angle variable, degree |
| $\theta_c$ | angle range covered by a light spot from a ray cone, degree |
| $\theta_l$ | parallel misalignment, degree |
| $\theta_{rsp}$ | circumferential range of a slice on receiver, rad |
| $\theta_s$ | circumferential angular displacement of sundisk, rad |
| $\theta_{ti}$ | angular displacement of slices on trough from z axis, mrad |
| Π | surface neighborhood |
| $\tau$ | formal parameter |
| Φ | function of sunshape model, dimensionless |
| $\phi$ | auxiliary angle variable, rad |
| $\psi$ | local contribution from a slice to the receiver, dimensionless |
| $\psi_r$ | gobal contribution from a slice to the receiver, dimensionless |
| $\psi_s$ | one-dimensional function of sunshape model, dimensionless |
| $\psi_{sl}$ | transformed sunshape, dimensionless |
| Ω | plane |
| $\omega$ | angle variable, degree |

*Subscripts*

| | |
|---|---|
| *a* | of the actual band |
| *b* | basic |
| *D* | from discretization |
| *k* | order number of the researched item |
| max | maximum |
| *M* | from misalignment |
| *rk* | arbitrary coordinate on receiver in the band surface neighborhood |
| *rkm* | middle of the surface neighborhood on receiver |
| *s* | function of sunshape |
| *sd* | placed on sundisk |
| *sp* | of an arbitrary band |
| *t* | on the reflection band on trough |
| *tk* | arbitrary coordinate on trough in the band surface neighborhood |
| *tkm* | middle of the band surface neighborhood on trough |
| *tr* | placed on trough |
| *w* | aperture width |

and Monte Carlo ray-tracing (MCRT) method. MCRT method was the most widely used for calculations of the irradiative boundary conditions (Cheng et al., 2013; Cheng et al., 2014; Cheng et al., 2012; Cheng et al., 2010; He et al., 2011; Song et al., 2014; Wirz et al., 2012). Compared to MCRT, FEM uses a uniform algorithm to create rays. Various commercial software programs based on ray-tracing methods, such as TracePro and SolTrace, have been used to establish the optical model of PTC systems. Because ray-tracing methods work on three dimensional (3D) space models, they require complicated 3D modeling and mass calculation. He et al. utilized 3D MCRT method to calculate the solar energy flux distribution as the boundary condition of the heat transfer model of a solar collector by tracing approximately 5E+7 rays and spending 250 s to obtain flux curve of sufficient accuracy (Cheng et al., 2012). Jiang et al. applied 3D FEM to flux distribution analysis, in which the standard deviation and computational time are respectively 0.3suns and 40 s with 8E+5 total grids(Jiang et al., 2010).

Researchers have investigated measures to reduce the amount of calculation. The characteristic of axial flux distribution was the basis of the succinctness. Almanza et al. built an experimental PTC platform and found that the deflection of a 2.9 m-long section was approximately 6.5 cm (Rafael et al., 1997), which would enlarge the circumferential temperature difference. Flores and Almanza et al. applied the bimetallic Cu-Fe wall receiver to increase the thermal conductivity to reduce the deflection (from 7 cm to 15 mm in the same system) (Flores and Almanza, 2004). Khanna and Singh et al. found an analytical expression to investigate the flux distribution of a deflected receiver (Khanna et al., 2013), with an end effect (Khanna and Sharma, 2015), based on the LS3 experimental platform. As a result, if the receiver is not eccentric, the axial variation can be neglected. Furthermore, the end effects at the extremes of a row of trough concentrators are case specific and typically small during the principal hours of solar collection (Naum et al., 2013). The translation symmetry of the system indicates that the calculation can be converted into a 2D mathematic process. Actually, one-dimensionalised modeling of a trough mirror of PTC has been achieved in calculation. It shows that the CPU running time is shorter and the computation effort is lower than that of the traditional Monte Carlo ray-tracing method (Liang et al., 2017). Several authors have suggested improvements in the optics of the parabolic-trough collectors utilizing the 2D method. Fraidenraich et al. summarized the exact analytic flux distribution using a 2D model including a parabolic trough with a