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Development of an analytical method and its quick algorithm to calculate the solar energy collected by a heliostat field in a year

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ABSTRACT

In this paper, we firstly propose an analytical equation to calculate the energy collected by the heliostat field. A ray tracing method is developed based on the analytical equation. Then we introduce three approximations to reduce computation spending, and estimate the errors caused by these approximations. A fast and accurate algorithm is developed with the three approximations to calculate the energy collected by the heliostat field over a year. It was compared with the ray tracing results, which shows good consistency with them. With the method, the energy collected and efficiency of each heliostat in a year can be computed exactly and rapidly, the difference between the method and ray tracing method is less than 0.1% for the energy collected by a heliostat over a day. It needs only about 0.1% computation time used by ray tracing method to calculate the intercept factor of a heliostat at a moment, and 2.67 h to compute the annual collected energy of PS10 heliostat field by using one CPU of i3 processor when the time span for integration is 5 min and each heliostat is calculated.

1. Introduction

In order to optimize the design of solar tower system, a reliable approach should be found to calculate the solar energy collected by the heliostat field in a year [1] because the diurnal and seasonal movement of earth affects the optical efficiency as well as the radiation intensity of the solar energy. There are hundreds or thousands of heliostats in a solar tower system. The collected energy of the system should be estimated from integration of reflected energy of each heliostat received by the absorber over a year. The reflected energy of a heliostat received by the absorber at a time is related to many factors including the direct normal irradiance, the cosine factor of heliostat, the shading effect of other heliostats and the tower, the reflectivity of heliostat, the blocking effect that reflected sunlight fails to reach the absorber caused by other heliostats, the absorbance of atmosphere to the reflected rays, the intercept factor of receiver, and the absorptivity of absorber [2].

The ray-tracing program is often used to calculate the collected energy of a heliostat at a moment accurately and flux distribution at the receiver such as MIRVAL [3], SOLTRACE [4], STRAL [5], HFLD [6] as well as the other solar concentrators [7,8]. We need to trace millions of rays of each heliostat at a moment. The large amount of calculation makes it difficult to be applied to the precise calculation of energy collected by the solar tower system in a year. They are often applied to validate the other methods in performance calculation and optimization of the solar central receiver system [2].

The second method is to assume a function to calculate the flux distribution produced by a heliostat at the receiver and then to calculate the annual energy collected by the heliostats through integration of the flux, such as UNIZAR [9] and HFCAL [10]. They are rather quick, and calculations for more instants of moments can be applied, for example, Noone et al. calculate about ten instants of time in average of every day of a year [2] with the similar method. However, recent evaluation to the UNIZAR and HFCAL shows that maximum absolute error can reach about 9% to predict the measured data [11].

The third method is to establish a function for integration to calculate the flux distribution at the receiver with some approximations, then to calculate the annual energy collected by solar tower system through integration of the flux over the receiver such as UHC [12]; DELSOL [13], and FIAT LUX [14]. Many different functions have been established [1,10,11,15–18]. In these methods, different approximations were introduced due to the huge computation including the following aspects for calculation of energy collected by the solar tower system in a year [19]:

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0196-8904/

Nomenclature

a, b and c	the parameter for calculating absorptivity, transmittance or reflectivity considering the incident effect
$B(\theta)$	distribution function of reflected sun brightness ($W/m^2/rad$)
D	the integral range which is determined by the range of the receiver projection on the reference plane
d	the distance from the center of heliostat to the center of absorber (km)
DNI	the direct normal irradiance (W/m^2)
E	the energy collected by the whole heliostat field in a year (J/m^2)
f_{at}	the atmospheric attenuation factor
f_{bs}	the blocking and shading factor of heliostat
f_{bsP}	the blocking and shading factor of point P
f_{rec}	the absorptivity of absorber
$I(i,t)$	the flux power collected by the ith heliostat at a given moment (W/m^2)
N	the number of heliostats in the tower field
P	flux power collected by the whole heliostat field at a moment (W/m^2)
S	the projected area of mirror under Direct Normal irradiance (m^2)
t	time (hour)
θ	radial angular displacement or angular displacement in transverse direction (rad)
φ	one coordinate in cylindrical coordinate system (rad)
λ	the incidence angle (rad)
λ_i	the incidence angle of central sunlight on the ith heliostat (rad)
ρ_i	the reflectivity of the ith heliostat
η	the optical efficiency without blocking and shading
η_o	the optical efficiency of a heliostat
η_p	the optical efficiency of a point on the heliostat

(a) The effective brightness distribution is approximately described by a Gaussian function to compute the flux density distribution over the absorber surface for collected energy calculation.
(b) Assuming the intercept factor, the reflectivity of heliostat, etc. of reflected ray at each point of the heliostat are equal. The shading and blocking factor are considered approximately to be unrelated to the intercept factor and reflectivity of reflected ray at each point of the heliostat.
(c) Assuming the reflectivity of heliostat and the absorptivity of absorber are constant and unrelated to the incidence angle.
(d) In order to reduce the computation and speed up the calculation procedure, it is often replaced by several heliostats to compute energy collected which represents the whole heliostat field.
(e) Choosing a few representative moments in a year and calculate the energy collected by several representative heliostats at these moments, and then use it to evaluate annual collected energy. Due to the computer capacity, the early codes only calculate the intercept factor of one instant of time (normally the design point) and the annual collected energy is recalculated by "scaling" the results of a detailed initial performance calculation [12,20]. Recent results shows there exists about 7.2% relative difference [2] between the two algorithms (64.01% vs 68.97%).

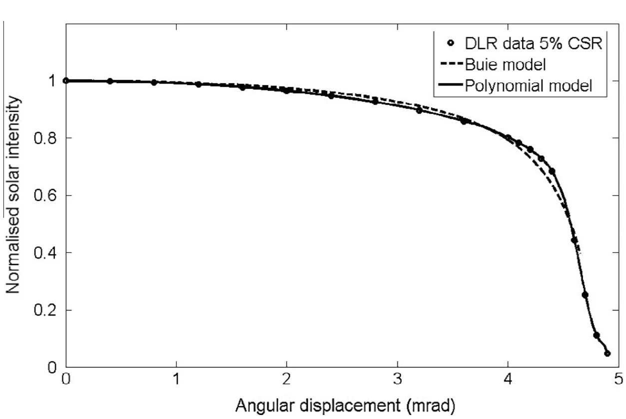

Fig. 1. Radial distribution of solar brightness.

As the annual energy collected by the heliostat field is calculated repeatedly, a quicker but less precise calculation is more preferred in optimizing the solar central receiver system, so more approximations are often applied in optimization than performance calculation.

In the present paper, we proposed an analytical equation which considers various factors to calculate the annual energy collected by the heliostat field in a new view. We introduce three approximations to reduce computation spending, develop a numerical algorithm with Gauss–Legendre Integration method, and estimate the computational errors caused by these approximations. We developed a ray tracing program bases on the analytical equation for evaluation of the numerical method.

2. Methodology

2.1. Calculation principle of intercept factor and energy collected of heliostat

If $B(\theta)$ is a normalized distribution function of reflected sun brightness, f_{at} is the atmospheric attenuation factor, f_{rec} is the absorptivity of absorber, the optical efficiency η_p of any point on the heliostat without shading or blocking can be calculated as following [21]:

$$\eta_P = f_{at} * f_{rec} * \gamma_P = f_{at} * f_{rec} * \iint_D B(\theta) d\varphi \sin\theta d\theta \quad (1)$$

where D is the integral range which is determined by the range of the receiver projection on the reference plane. If the blocking and shading are considered by other heliostats, then the optical efficiency η'_p of any point on the heliostat can be calculated as following:

$$\eta'_P = f_{at} * f_{rec} * \gamma_P = f_{at} * f_{rec} * \iint_D f_{BS}(\theta,\varphi) B(\theta) d\varphi \sin\theta d\theta \quad (2)$$

where $f_{BS}(\theta,\varphi)$ is the blocking and shading factor of a ray which is related to the direction of the ray. It can be calculated as following: