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A new method for the design of the heliostat field layout for solar tower power plant

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ABSTRACT

A new method for the design of the heliostat field layout for solar tower power plant is proposed. In the new method, the heliostat boundary is constrained by the receiver geometrical aperture and the efficiency factor which is the product of the annual cosine efficiency and the annual atmospheric transmission efficiency of heliostat. With the new method, the annual interception efficiency does not need to be calculated when places the heliostats, therefore the total time of design and optimization is saved significantly. Based on the new method, a new code for heliostat field layout design (HFLD) has been developed and a new heliostat field layout for the PS10 plant at the PS10 location has been designed by using the new code. Compared with current PS10 layout, the new designed heliostats have the same optical efficiency but with a faster response speed. In addition, to evaluate the feasibility of crops growth on the field land under heliostats, a new calculation method for the annual sunshine duration on the land surface is proposed as well.

1. Introduction

The solar tower power plant is known as one of the least expensive methods to produce solar electricity on a large scale. In solar tower power plant, the solar radiation is firstly concentrated and reflected by heliostat field onto a receiver atop tower, and then in the tower the very dense solar power is translated into thermal power to generate electricity. The heliostat field is a pivotal subsystem in solar power towers because it typically contributes ~50% [1] to the total cost and causes power loses by ~40%. Therefore, the design and optimization of heliostat field layout are very important.

The design and optimization of heliostat field layout are usually realized by using special codes. Since 1970's codes such as DELSOL3 [2], WinDELSOL1.0 [3], SOLTRACE [4], MUEEN [5], SENSOL [6] and so on have been developed for this purpose. The Monte Carlo ray tracing method is normally employed for establishing the mathematical model and calculating the optical efficiency which is usually consisted of the reflection efficiency, the cosine efficiency, the interception efficiency, the blocking and shadowing efficiency and the atmospheric transmission efficiency [7]. The configuration of heliostat field layout is usually determined by the arrangement type [8], the distance between heliostats, the row distance, the boundary constraint, the tower height and the receiver aperture. The boundary constraint is one of the most important configuration parameter of the heliostat field. For radial stagger field layout, the angular boundary is normally constrained by extended angle which needs to be inputted by designer, and the radial boundary is constrained by tower height and receiver aperture height, for example the DELSOL3 and the MUEEN codes. This method is simple but the heliostats have a low optical efficiency. In the WinDELSOL1.0 code, the boundary is constrained by the efficiency factor which is the product of the annual cosine efficiency, the annual atmospheric transmission efficiency of heliostat and the annual interception efficiency of receiver. M. Sanchez [9] presented a method for the design of heliostat field layout based on yearly normalized energy surfaces, but the annual cosine efficiency, the annual interception efficiency, the annual blocking and shadowing efficiency and the annual atmospheric transmission efficiency are all needed to be calculated repeatedly during placing heliostat and analyzing efficiencies. In particular, the computing quantity of the annual interception efficiency is very high due to the millions time of ray tracing during the design and optimization. In this work, a new method for the design of heliostat field layout is presented. In the new method, the field boundary is constrained by the receiver geometrical aperture and an efficiency factor. The annual interception efficiency doesn't need to be calculated when place heliostat to save the computing quantity. A new code (HFLD) [10,11] has also been

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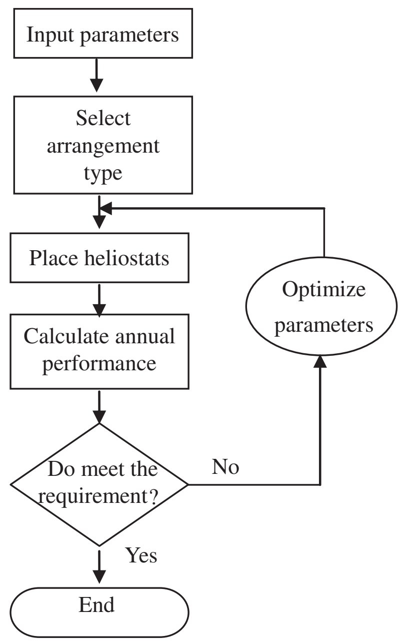

Fig. 1. Flow chart of the design of the heliostat field layout.

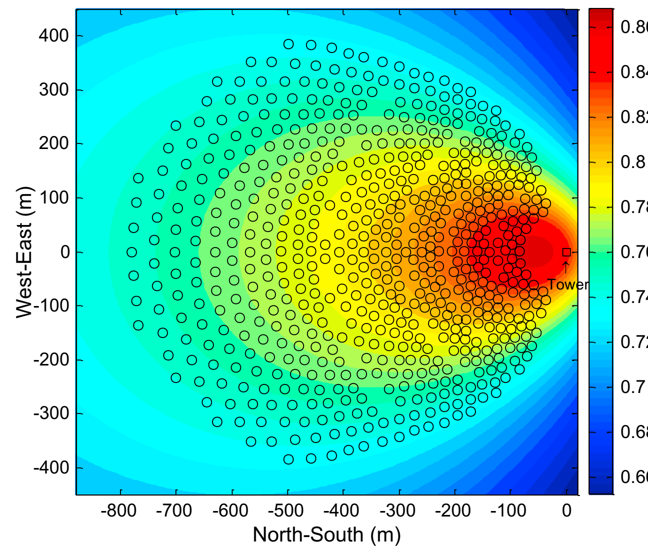

Fig. 3. Distribution of the efficiency factor in the PS10 field land.

developed based on the MATLAB tools and validated by using current PS10 field [12–14] which is designed by the WinDELSOL1.0 code. A new layout for the PS10 plant has been designed by using the new code. Finally, in order to calculate the distribution of sunshine duration on the land surface under heliostats which can not be done by traditional codes, a new method has been developed to evaluate the feasibility of crops growth on the land in this paper.

2. Boundary constraint of heliostat field layout

The flow chart of the design of the heliostat field layout is shown in Fig. 1. The heliostat field layout can be optimized to meet the certain design requirements by using the parameter search algorithm [10]. The values of parameters such as the tower height, the receiver tilt and size, the distance between the heliostats which determine the layout are allowed change within a design range, and after that, the annual performance are calculated for each one of the total possible combinations of parameters. The optimum layout can be then selected among all the possibilities. In particular, the location of the field can be pre-selected according to the local solar radiation resource. The number of heliostat strongly depends on the design requirement of the power output, the local solar radiation resource and the optical efficiency of the heliostat field. In the design process an initial value of the number of heliostat is given by user, and then a field layout is made and optimized and the optical efficiency is calculated. After that the power output of the field is evaluated according to the local solar radiation resource. The number of heliostat can be selected when the power output meets the design requirement.

For the radial staggers field layout, assuming that the location of the field, the tower height and the number of heliostat are fixed, the layout is mainly determined by the boundary constraint, the radial and angular distances between heliostats and the distance between the first row and the tower base. The cosine efficiency, the interception efficiency and the atmospheric transmission efficiency of system strongly depend on the boundary constraint. So the efficiency of system can be increased by optimizing the boundary constraint. The system efficiency also strongly depends on the blocking and shadowing efficiency which depends on the radial and angular distances between heliostats and can be calculated by using ray tracing method. The details about the blocking and shadowing calculations were presented in the published paper [10]. To increase the blocking and shadowing efficiency, the radial and angular distances between heliostats need to be optimized also by using the parameter search algorithm.

An improved boundary constraint method for the heliostat field layout has been proposed. The field boundary is constrained by the receiver geometrical aperture and an efficiency factor which is the product of the annual cosine efficiency and the annual atmospheric transmission efficiency. The design starts from inputting a proper boundary factor, followed by the calculation of the efficiency factor

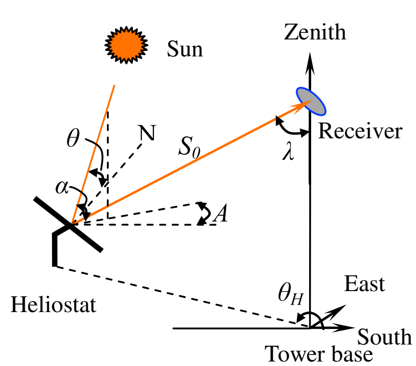

Fig. 2. Coordinate system of the heliostat field layout.

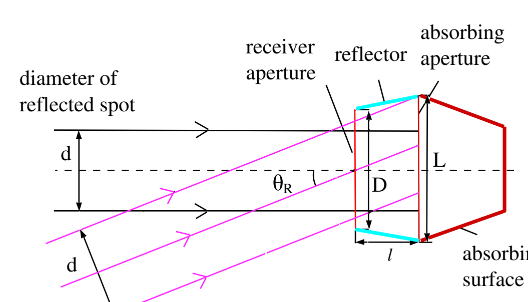

Fig. 4. Definition of acceptance angle of the cavity receiver.

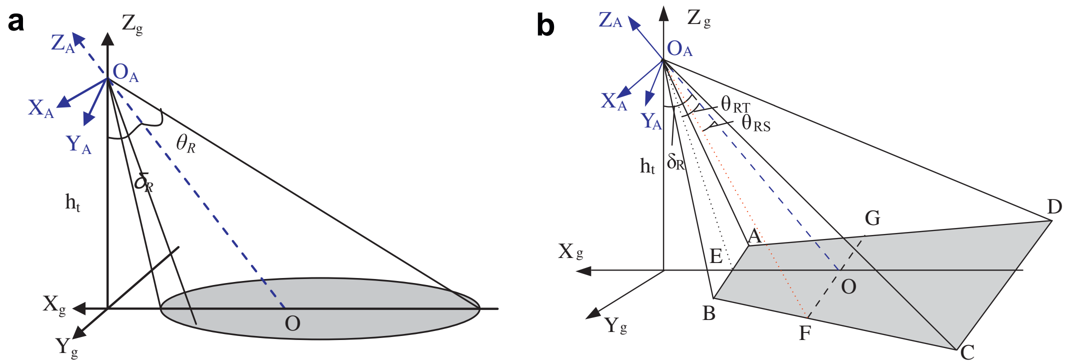

Fig. 5. Projection boundary on the field land from receiver aperture. (a) Circular aperture projection. (b) Rectangular aperture projection.

and then a comparison between the calculated result and the inputted factor. If the calculated value is found to be larger than the inputted one, then the heliostat is judged whether it locates within the constrained boundary or not. If it does, the heliostat will be placed. Otherwise, the heliostat should be placed in a next row. The new method can make sure the heliostats are placed within those zonings where the annual cosine efficiency, the annual interception efficiency and the annual atmospheric transmission efficiency of heliostat are higher. It should be noted that the calculation of the annual interception efficiency is not needed anymore when place the heliostats for the new method. The boundary constraint can be optimized by using the parameter search algorithm.

The cosine efficiency of a heliostat equals to the cosine of incidence angle θ relative to the heliostat center and is given by below formula [10]

$$\eta_{\cos} = \frac{\sqrt{2}}{2}\left[\sin\alpha\ \cos\lambda - \cos(\theta_H - A)\cos\alpha\ \sin\lambda + 1\right]^{\frac{1}{2}} \tag{1}$$

where, α is the solar altitude angle [15], A is the solar azimuth angle [15], λ is the angle between the reflected ray incident on the heliostat center and the vertical direction, θ_H is the azimuth angle of the heliostat relative to the tower base (see Fig. 2). By integrating $\eta_{\cos}$ over a year and making average, the annual cosine efficiency of the heliostat can be obtained.

The atmospheric transmission efficiency strongly depends on the weather condition and the distance between the heliostat and the receiver. For a visual distance of about 40 km, the atmospheric transmission efficiency can be calculated simply as a function of the distance between the heliostat and the receiver in meters [16] as follow

$$\eta_{at} = 0.99321 - 0.0001176 \times S_0 + 1.97 \times 10^{-8} \times S_0^2\,(S_0 \le 1000\ \text{m})$$

$$\eta_{at} = e^{-0.0001106 \times S_0}\quad (S_0 > 1000\ \text{m}) \tag{2}$$

where, S_0 is the distance between the heliostat and the receiver (see Fig. 2).

Taking the PS10 field as an example, the efficiency factor is calculated by code HFLD. The distribution of the efficiency factor on the field land is as shown in Fig. 3.

The field boundary is also constrained by the cavity receiver aperture. The receiving angle of cavity receiver is defined as the maximum angle so that any reflected ray of heliostat field with an incident angle less than it can be received by the receiver. This definition of the receiving angle is similar to the collecting angle of the compound parabolic concentrator in non-imaging optics [17]. The formula for calculating the receiving angle of the cavity receiver has been derived as follows

$$\theta_R = \arcsin\left(\frac{-2dl + L\sqrt{4l^2 + L^2 - d^2}}{4l^2 + L^2}\right) \tag{3}$$

where, d is the diameter of the reflected spot of heliostat field, D is the diameter of the receiver aperture ($D \ge d$), L is the diameter of the absorbing aperture ($L \ge D$), l is the distance between the receiver aperture and the absorbing aperture (see Fig. 4). When the receiver aperture equals to the absorbing aperture ($l = 0$, $L = D$), the formula of receiving angle can be written as

$$\theta_R = \arccos\left(\frac{d}{D}\right) \tag{4}$$

The receiver aperture usually has a shape of circle or rectangle, therefore the corresponding projection boundary on the field land is ellipse or trapezium as shown in Fig. 5. Where δ_R is the tilt angle of the aperture plane relative to the vertical direction, θ_R is the receiving angle of the circular aperture receiver, θ_{RT} and θ_{RS} are the meridian and sagittal receiving angles of the rectangular aperture receiver respectively, h_t is the altitude of the aperture center relative to the horizontal plane.

For the circular aperture, the equation of projection ellipse is given by,

$$y^2 + (\cos\delta_R x + \sin\delta_R h_t)^2 - \tan^2\theta_R(\sin\delta_R x - \cos\delta_R h_t)^2 = 0 \tag{5}$$

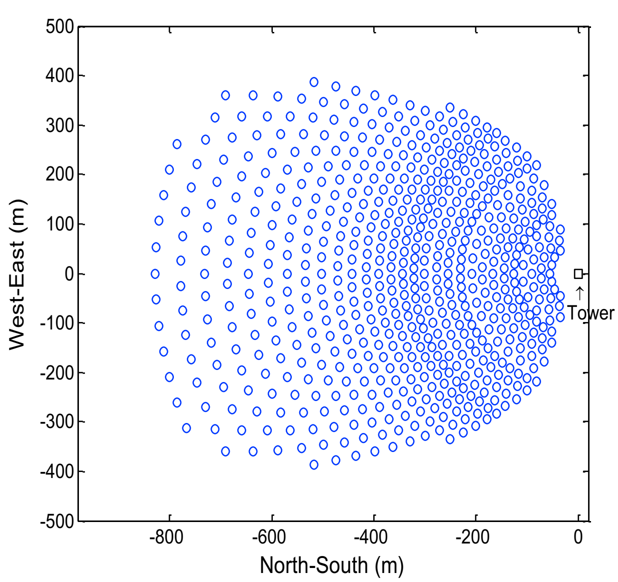

Fig. 6. Pattern of the new designed layout by the code HFLD at the PS10 location.

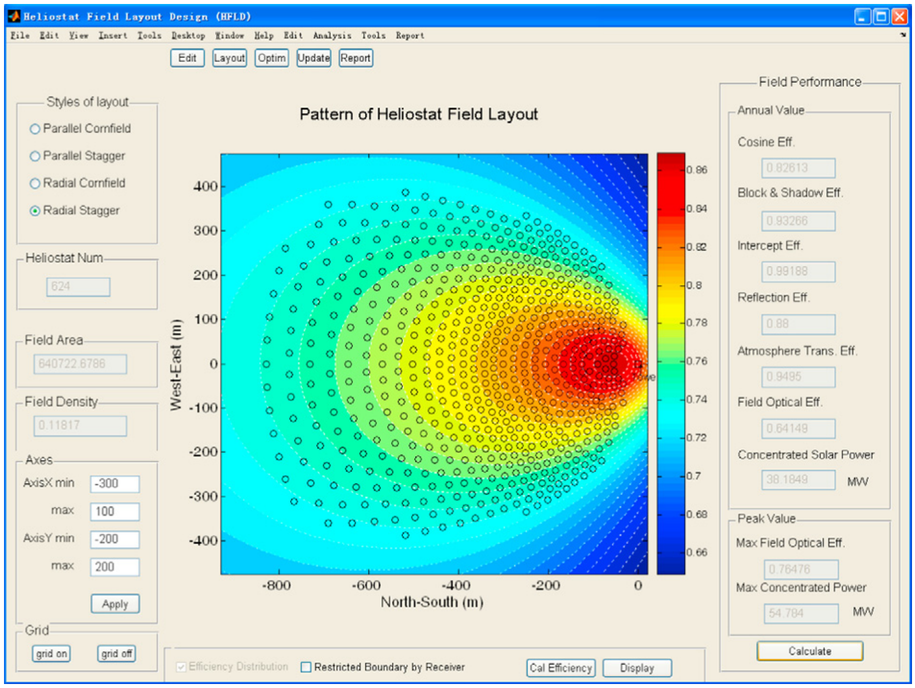

Fig. 7. Calculated annual performance of the new layout by using the HFLD code.

For the rectangular aperture, according to the geometrical relationship in Fig. 5(b) the coordinates of the point A has been derived as follows,

$$\begin{cases} x_A = \dfrac{h_t(\tan\theta_{RS}\ \cos\delta_R - \sin\delta_R)}{\cos\delta_R + \tan\theta_{RS}\ \sin\delta_R} \\ y_A = \dfrac{-\tan\theta_{RT} h_t}{\cos\delta_R + \tan\theta_{RS}\ \sin\delta_R} \end{cases} \tag{6}$$

The coordinates of points B, C and D can be calculated by using the same method.

According to the new method, the field boundary is constrained by the receiver geometrical aperture and the efficiency factor which is the product of the annual cosine efficiency and the atmospheric transmission efficiency. The heliostats can be placed in the areas with a higher optical efficiency and the annual interception efficiency does not need to be calculated when place the heliostats. Therefore, the total time for designing and optimizing heliostat field layout is saved significantly.

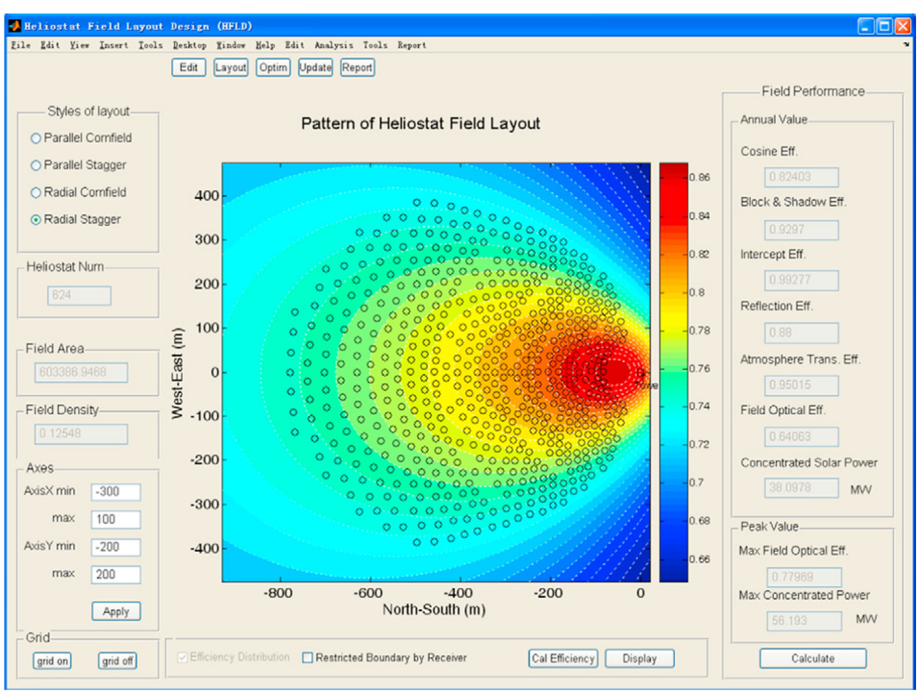

Fig. 8. Calculated annual performance of current PS10 layout by using the HFLD code.

3. Design of a new heliostat field layout

Based on the proposed boundary constraint method, a new code (HFLD) for the design of the heliostat field layout has been developed. The validation of the code has been confirmed by comparing with the published data of current PS10 field [11]. The PS10 field is consisted of 624 heliostats in an area of 12.84 × 9.45 m^2 and located at north latitude of 37.4 degrees. The reflectivity of mirror is about 0.88. The receiver is a cavity with a rectangular aperture of 13.78 m × 12 m. The tilt angle of the receiver is 12.5 degrees. The altitude of the receiver center is 100.5 m relative to the ground [12–14]. A new layout for the PS10 plant at the PS10 location has been designed by using the new code HFLD. The initial configuration parameters of the new layout are the same as above parameters of the PS10. The designed optimal tilt angle of the receiver is 17 degrees. The new layout pattern is shown in Fig. 6.

The annual performance of the new layout has been calculated as shown in Fig. 7. By using the same parameters, the annual performance of the current PS10 layout is calculated as well by using the HFLD code as shown in Fig. 8. The comparison of performance between the new layout and the PS10 layout is shown in Table 1.

As can be seen from the Table 1, the system performance of the new layout is as good as that of current PS10 layout. Therefore, the new method is feasible for the design of heliostat field layout. Compared with the WinDELSOL1.0 code or the presented method in reference [9], the new code is expected to have a faster speed because the repeated calculations for the annual interception efficiency are eliminated during the design and optimization.

4. Distribution of sunshine duration on the land surface

The large scale solar tower plants are to be built in the desert of Gobi due to their enormous occupation of the land. However, some demonstrating solar tower plants are built in arable land like PS10 and PS20 etc. in Spain. To maximize the utilization of land, suitable crops can be considered to be planted on the land under heliostats. To evaluate the feasibility of the crop growth, a method for calculating the annual distribution of sunshine duration on the land surface is proposed.

By using ray tracing, the coordinates of intersection points between the land surface and the incidence rays passing the heliostat surface have been derived.

$$\begin{aligned} x_g &= \sin A_H x_m + (\cos A_H \ \cos E_H - \sin E_H ctg\alpha \sin A)\cdot y_m \\ &\quad -X_{gH} - Z_{gH} ctg\alpha \sin A \\ y_g &= \cos A_H x_m - (\sin A_H \ \cos E_H + \sin E_H ctg\alpha \sin A)\cdot y_m \\ &\quad +Y_{gH} - Z_{gH} ctg\alpha \sin A \end{aligned} \tag{7}$$

where, (x_m, y_m) are the coordinates of points in the heliostat surface, (X_{gH}, Y_{gH}, Z_{gH}) are the coordinates of heliostat on the field land,

Table 1
Comparison of performance between the new layout and the PS10.

Field performance	PS10 layout	New layout	Difference
Annual mean field optical efficiency	64.06%	64.15%	0.09%
Annual mean cosine efficiency	82.4%	82.6%	0.2%
Annual mean blocking and shadowing efficiency	93.0%	93.3%	0.3%
Annual mean interception efficiency	99.3%	99.2%	−0.1%
Annual mean atmospheric transmission	95.02%	94.95%	−0.07%

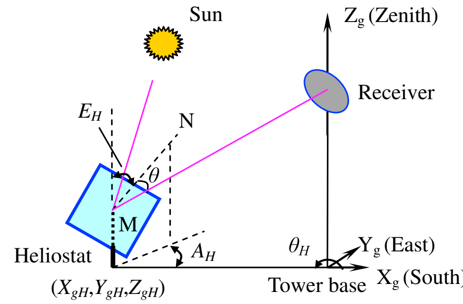

Fig. 9. Coordinates of a heliostat with the azimuth-elevation tracking on a field land.

A and α are the solar azimuth and altitude angles respectively (see Fig. 2), A_H and E_H are the azimuth and tilt angles of heliostat with the azimuth-elevation tracking respectively (see Fig. 9).

When the sun altitude is low enough, the shadow caused by the heliostat on the land might overlap with each other which should be considered in calculation. The shadowing area of the land surface has been derived as,

$$\text{Field}_{\text{shadow}} = \sum_{i=1}^{N} \frac{A_{\text{helio}} \cos\theta}{\sin\alpha} \eta_{\text{shadow}} \tag{8}$$

where, A_{helio} is the area of single heliostat, N is the total number of the heliostat, η_{shadow} is the shadowing efficiency of single heliostat [10], α is the solar altitude angle (see Fig. 2), θ is the incidence angle on the heliostat center (see Fig. 2).

The calculation procedure for sunshine duration on the land surface under heliostats is described as follows. Firstly, each heliostat is divided into $n \times n$ elements with equal area. The coordinates of intersection between the land surface and the incidence rays passing the element center of the heliostat are calculated by using equation (7). Next, the land surface is divided into $k \times l$ equal facets. A full one matrix **B** is generated whose elements are corresponding with all facets of the land surface. If the intersections between the land surface and the incidence rays passing heliostat surface locate within a facet of the land, the corresponding element of the matrix **B** is set as 0. Then, in the observed period, the first and second steps are repeated for each sampling time point which is corresponding with single matrix **B**. After calculations, all

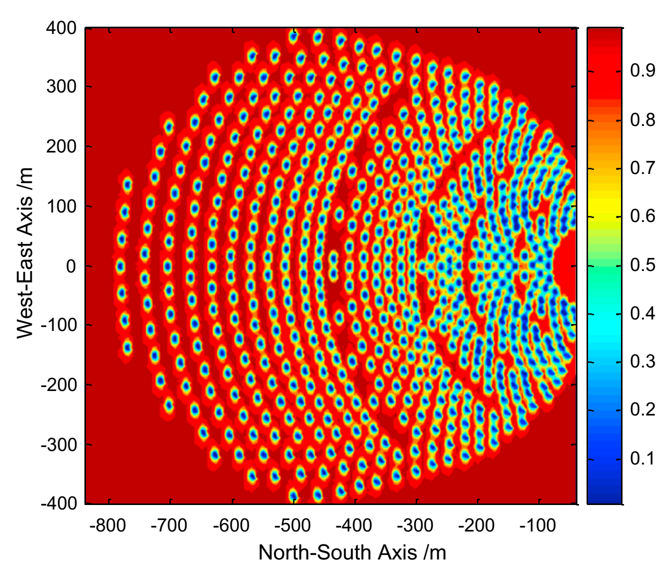

Fig. 10. Distribution of relative sunshine duration of the PS10 field land.

matrixes are cumulated and a new matrix $\mathbf{B}'$ is generated. The elements of the new matrix $\mathbf{B}'$ also are corresponding with all facets of the land surface. If the number of sampling time point is u and the element value of matrix $\mathbf{B}'$ is v, then duration of sunshine of the corresponding facet of field land can be given by

$$T_{\text{shine}} = T\frac{v}{u} \tag{9}$$

where, T_{shine} is relative sunshine duration on the land surface, T is sunshine duration without the heliostat layout.

Taking the PS10 field as an example, the distribution of sunshine duration on the land surface is calculated by the code HFLD and is shown in Fig. 10. The observed period is from the 81st day to the 173rd day of a year.

Generally, the physiological characteristics of crop should be considered like height and volume. The distribution of sunshine duration in a certain range of height of field land can be calculated by above method.

5. Conclusions

In order to place the heliostats with a higher optical efficiency, a field layout method by using a standard factor called YNES was proposed, but the annual optical efficiency of heliostat needs to be calculated by using ray tracing during placing and analyzing the field layout, which takes an enormous time. To address this issue, a new method of field layout has been proposed in this paper. In the new method, the field boundary is constrained by the receiver geometrical aperture and an efficiency factor. By using the new method, the heliostats can be placed with a higher optical efficiency as well as a faster speed due to the elimination of the calculation of the annual interception efficiency. Based on the new method, a new code, named HFLD, has also been developed and a new layout for the PS10 plant at the PS10 location has been designed by using the new code. Compared with current PS10 layout, the system performance of the new layout is found to be as good as that of current PS10 layout. Therefore, the new method for heliostat field boundary constraint is proved to be feasible. In addition, to increase the utilization of field land and evaluate the feasibility of the crop growth in field land under heliostat layout, a new calculation method for annual distribution of sunshine duration is presented in this paper.

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