International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Design of Heliostat Field for Small Scale Central Receiver System

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Accepted 12 March 2017, Available online 16 March 2017, **Special Issue-7 (March 2017)**

Abstract

Central receiver system (CRS) is one of the type of concentrated solar power (CSP) technology which consists of heliostat field, receiver and power generation unit. Heliostats are nothing but the mirrors which concentrate solar radiation at one point on receiver which is located at the top of a high tower. Out of the total cost of system heliostat field contributes 50% and leads to about 47% of the annual energy losses. So placing of heliostats in field is most important in order to minimize optical losses and indirectly minimizes energy losses. In this Paper work, heliostat field is designed for no shadowing, blocking losses and optimized cosine efficiency for small field area specifically for Pune location. An algorithm is developed for heliostat distribution in heliostat field as per design using a MATLAB.

Keywords: *The solar power tower plant, Heliostat Field, cosine efficiency, shadowing and blocking losses.*

1. Introduction

The central receiver system (CRS) is highly effective method to get a high concentration of solar flux to generate electric power as well as for other process industries applications. This system uses heliostats (plane reflective mirrors) which track the sun and reflect sunlight incident on it towards receiver located at the top of high tower. The solar flux incident on receiver heats a heat transfer medium or fluid in heat exchanger which is connected with the receiver. Temperature ranging from 500°C to 1000°C can be obtained in heat transfer medium. This heated fluid is then used to produce the steam which is ultimately used to generate electric power or directly used in process industries as per requirement.

The central receiver plant consists of heliostat field, tower and receiver, heat exchanger or any other heat transfer device, turbine (in case of power generation), generator set etc. Out of all these components heliostat field layout design is most important, costly and time consuming process. The performance of the heliostat field is expressed in terms of the optical efficiency, which is defined as a ratio of the net power incident on the receiver to the power incident normally on the whole heliostat field. Optical efficiency is also expressed in terms of optical losses and these losses include the cosine loss, shading and blocking losses, imperfect mirror reflectivity loss, atmospheric attenuation, and receiver spillage losses.

In a solar power tower plant, the receiver is also important component of CRS. It collects all reflected solar radiation from the heliostat field and transfer thermal energy to the heat transfer fluid. During radiation concentration on receiver surface local hot spots are generated which creates temperature gradients on surface. These temperature gradients induces thermal stresses or mechanical stresses in receiver material and hence receiver life gets reduced. The flux distribution on receiver surface is depend on design of receiver, receiver material selection, type of heat exchanger used, type heat transfer fluid used or TES(thermal energy storage material) material used in heat exchanger. Distribution of the heat flux on the receiver surface is also depends on the performance of the heliostat field. Flux distribution on receiver surface (normal distribution) can be controlled to uniform distribution by defining several aiming points i.e. each heliostat has different aim point on receiver surface.

Siala and Elayeb [2001] reported a work on the graphical method for a no-blocking, radial staggered pattern heliostat field layout. With the use of this method MUEEN code has been developed in C++ for heliostat distribution in field such that they minimize blocking losses. Shadowing losses are not considered in their work.

Sa´nchez and Romero [2006] suggested a method to generate of heliostat field layout in central receiver systems on the basis of yearly normalized energy surfaces. In this work they found out highly energetic surfaces over the whole year in field layout and heliostat are placed accordingly. Optimization thus developed is cross validated against codes like Delsol.

The Campo algorithm presented in [2012] consists on a set of algorithms to create improved radial staggered layouts. As a first approach, an algorithm to define Dense Radial Staggered layouts is presented. In these layouts the radial spacing between adjacent rows is

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constant and azimuth spacing is calculated for each heliostat zone. Then, an azimuth expansion and radial expansion is proposed to alleviate the heliostat density and obtain fields with higher annual energy. The input parameters of the algorithm are the heliostat dimensions, the radius of the first row in the field, an additional separation distance between the center of two adjacent heliostats, and a reference blocking factor. The basic procedure defined in Campo places the first heliostat of even rows in the north axis (Y axis). The second heliostat of these rows is placed at distance of ΔAz from the first one in clockwise direction. The same procedure is used for the rest of the heliostats in the row. The odd rows' first heliostats are placed at ΔAz/2 from the Y axis (N) and subsequent heliostats are placed at distance of ΔAz from the previous one.

2. Heliostat field design

2.1 Cosine Losses

Cosine losses can be expressed in terms of "cosine efficiency" which is most important factor to design heliostat field layout. This efficiency is depends on sun's position (longitude and latitude) as well as position of each heliostat relative to the receiver. The heliostats track sun using two axis tracking mechanism in such way that normal to heliostat surface bisects the angle between the sun's rays and a normal to heliostat surface towards the tower. This can be explained by considering heliostats at two positions in a field as shown in Figure 1. From fig we can say that Heliostat A has a small cosine loss as compared to Heliostat B. This is because normal to heliostat A is exactly along the vector joining center of heliostat and receiver surface. For better cosine efficiency most of the heliostats are placed just opposite the sun. An equation to calculate cosine of angle of incidence is given as below

$$cos2\theta i = \frac{(Z_0-Z_1)sin\alpha - e_1 cos\alpha\ sinA - n_1 cos\alpha cosA}{[(Z_0-Z_1)^2+{e_1}^2+{n_1}^2]^{1/2}}$$

$$2\theta i = \cos^{-1}\frac{(Z_0-Z_1)sin\alpha - e_1 cos\alpha\ sinA - n_1 cos\alpha cosA}{[(Z_0-Z_1)^2+{e_1}^2+{n_1}^2]^{1/2}}$$

$$\theta i = \frac{1}{2}\left[\cos^{-1}\frac{(Z_0-Z_1)sin\alpha - e_1 cos\alpha\ sinA - n_1 cos\alpha cosA}{[(Z_0-Z_1)^2+{e_1}^2+{n_1}^2]^{1/2}}\right] \quad (1)$$

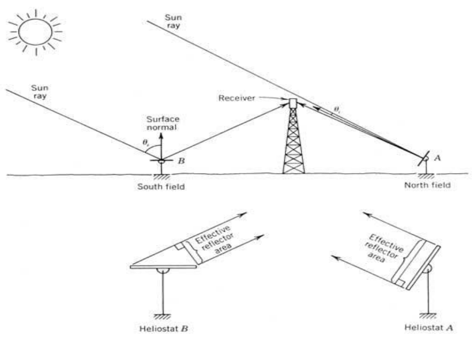


Fig.1 cosine efficiency comparison for Heliostat A and Heliostat B [Stine's,2008]

where α and A are the sun's altitude and azimuth angles respectively and *z, e,* and *n* are unit vectors along zenith, east and north direction respectively.

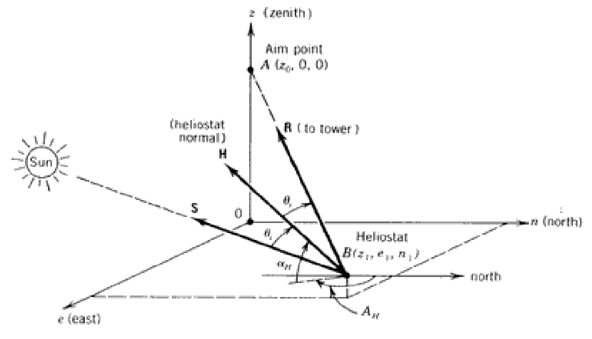


Fig 2 Co-ordinate system used for heliostat field[Stine 2008]

It is found that heliostats are generally placed in north field i.e. tower is on south side for better efficiency.

2.2 Shadowing and Blocking Losses

In central receiver systems, shadowing and blocking are two processes which also contribute to optical losses. These losses can also be expressed in terms shadowing and blocking efficiency. Determination of these losses is somewhat difficult in optical efficiency calculation. Shadowing efficiency is the ratio of shaded surface of heliostat to total heliostat surface and it occurs when a heliostat casts its shadow on a heliostat located behind it. Similarly blocking is defined as ratio of blocked surface of heliostat to total heliostat surface. In case of shadowing not all rays coming from sun are incident on heliostat while in blocking not all the rays reflected from heliostat reach the receiver. These two processes are explained in Figure 3.

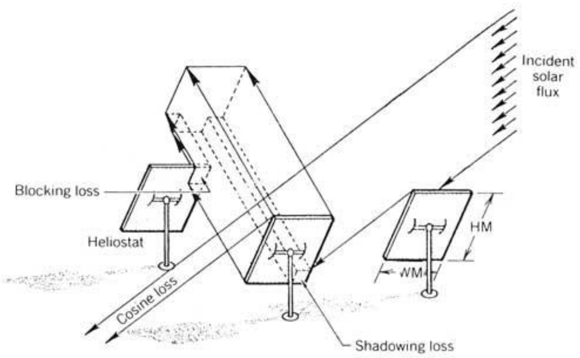


Fig 3 Shadowing and blocking of sun rays [Stine's,2008]

Among all field layout radial Staggered field is considered as most efficient which is shown in Figure 4. This field layout optimizes use of land as well as minimizes shadowing and blocking losses. In this field layout pattern heliostats are highly denser near the tower and this density decreases as we go away from it. If spacing between heliostats is too much large then additional heliostat are added in spacing and new heliostat group started.

Heliostat packing density is one of the factor which indicate efficiency of heliostat field and this can be defined as the ratio of mirror area to field area. The average heliostat packing density value is fall in between the range of 0.2 to 0.25.

The radial spacing ΔR and the azimuthal spacing ΔA, explain in Figure 4, are given as below assuming high-reflectance heliostats (about 90 percent reflectivity) [Stine's ,2008].

$$\Delta R=H(1.44\cot\theta_L-1.094+3.068\theta_L-1.125\theta^2_L)\ldots(m)$$

$$\Delta A=W(1.749+0.6396\theta_L+\frac{0.2873}{\theta L-0.04902}\ldots..(m) \quad (2)$$

Where, '*H*' and '*W*' are the height and width of the heliostat, respectively as shown in Figure 3. The angle θ_L is the altitude angle to the receiver from the heliostat location and can be calculated as

$$\tan\theta_L=1/r\ldots\ldots..(3)$$

where *r* is the normalized distance from the tower to the heliostat surface measured in terms of "tower heights."

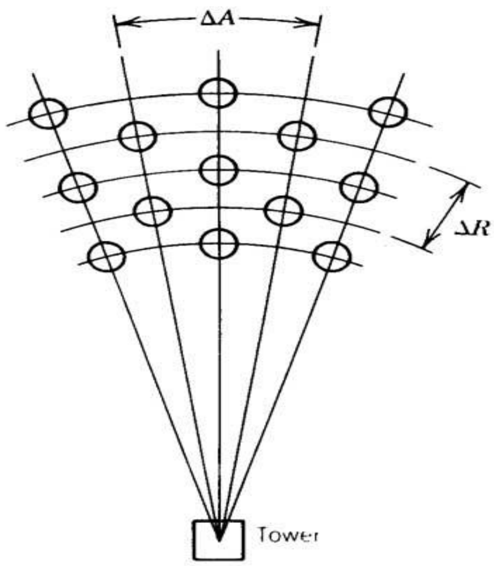


Fig 4 Radial Staggered Field Pattern [Stine's,2008]

2.3 Atmospheric Attenuation Losses

Many researchers working on field layout design suggest that heliostat field should be extend on north side of high tower. But there is limitation on distance from tower to receiver as most of radiations travelling from heliostat to receiver are get absorbed due to scattering and dust particle present in atmosphere.

Atmospheric attenuation losses are assumed by Vittitoe and Biggs (1978) for a clear day (23-km visibility) and a hazy day (5-km visibility). For a clear day with 23-km visibility, the atmospheric attenuation can be given as [Stine's 2008].

$$\tau_a=0.99326-0.1046S+0.017S^2-0.002845S^3 \quad (4)$$

where *S* is perpendicular distance from heliostat to receiver in kilometers. For a hazy day with only 5-km visibility, the atmospheric attenuation is given as [Stine's,2008]

$$\tau_a=0.98707-0.2748S+0.03394S^2 \quad (5)$$

Above expression used for atmospheric attenuation loss calculation are depend upon site location i.e. latitude and strongly depend on dust particles present in atmosphere. For clear day these losses are less compared to hazy day.

2.4 Tower Height

Optimum tower height is generally about 1/6 the length of the farthest heliostat in the field to the tower, as shown in Figure 5. With the farthest heliostat about 15 m away from the tower (approximate length of the field including the equipment area), the tower height is taken to be 1/6 of this value, or about 2.5m.

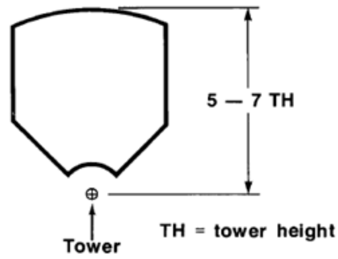


Fig 5 Optimal tower heights [Murray, 2012]

2.5 Tower Shadowing

Note that once the heliostat layout is designed, it is necessary to look at how the shadow casted by the tower onto the field affects the heliostats. Because the tower is very tall, it casts a large shadow. If this shadow covers a line of heliostats, total system energy output may get reduced. In order to figure out where the shadow will cast (angle μ), and its length (L), the solar azimuth and altitude angles must be known, as well as the tower height (H), as shown below.

The direction the shadow is pointing in the ground plane is related to the azimuth angle as shown in the top view. The shadow will always point (γs-180°) east of north. If this number comes out negative, the shadow is then pointing west of north (morning hours).

Therefore

$$\mu = \gamma s-180° \quad (6)$$

From the side view figure of tower, the length of the shadow will always be

$$L=H/\tan(\alpha) \quad (7)$$

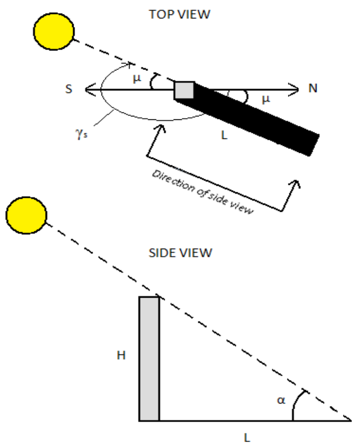


Fig. 6 Length of Tower Shadow [Murray,2012]

2.6. Algorithm for heliostat field layout design

The program begins with input parameters necessary to design a heliostat field namely filed and heliostat dimensions with maximum azimuth angle from solar angles database for 2017. The detail program script is provided in flow chart 1.

Design is focused mainly to avoid shadowing & blocking errors. The receiver height is calculated one sixth of length of heliostat filed determined as per availability of area. Normalized distance between receiver and heliostat is calculated based on the maximum angle of azimuth to avoid the longest possible shadow of receiver as per the angle data.

Azimuth and Radial spacing between the heliostats is calculated based on below formulae and further the coordinates for each heliostat are calculated.

Next step is to calculate Cosine efficiency to determine the ability of each heliostat positioned as per the coordinates calculated with respect to azimuth and radial spacing.

The elevation and azimuth angles data is collected for each day of 2017 from 8 am to 5 pm from the earthtools.com as per projected information. This angle database is then used to calculate the cosine efficiency for each heliostat and then the plot of heliostat positions with their respective cosine efficiency is represented in terms of color intensity as shown below in figure 7.

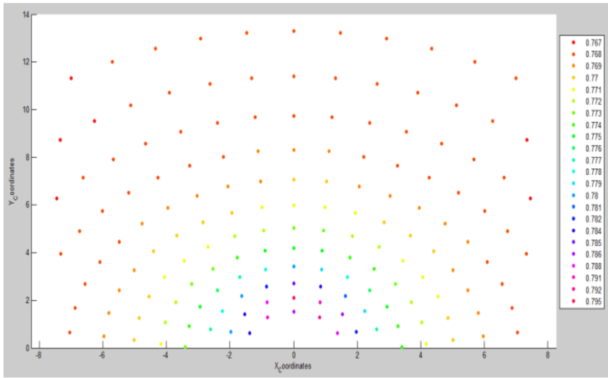
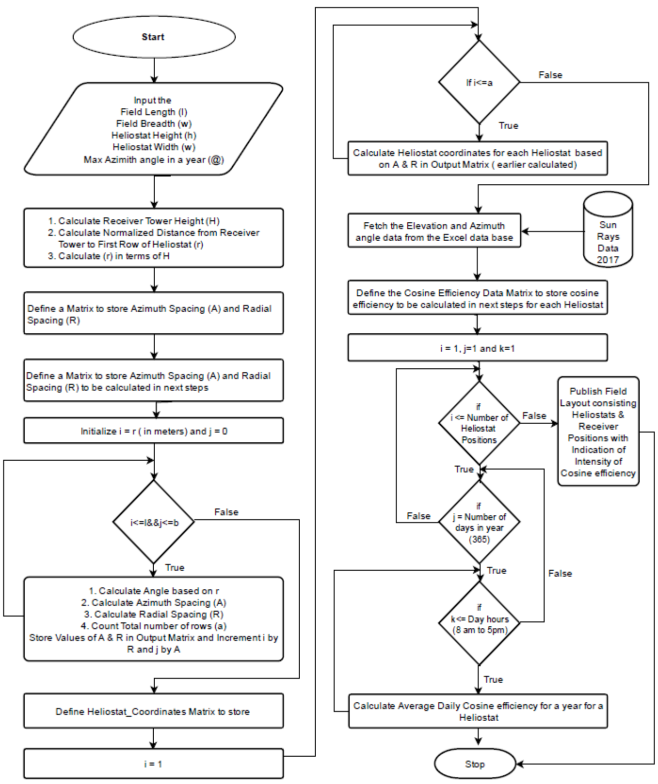


Fig 7. Heliostats distribution in field area



Flow Chart 1 Algorithm of Heliostat Field Layout Design Program in MATLAB

3. SolTrace Results

SolTrace software uses a Monte-Carlo ray-tracing method to simulate sunrays coming from sun and incident on CSP devices. This software is developed by the National Renewable Energy Laboratory (NREL). Co-ordinates of each heliostat obtained from MATLAB Program are used in SolTrace software to validate the proposed field layout design. Figure 8 and 9 shows a screenshot from a SolTrace simulation.

For simulation purpose Day of Year (DOY) and time consider is 355 i.e. 21st December and 8 am respectively. The reason is that on this day and time in Northern hemisphere the length of shadow is longest as compared to other days in year. So on this day and time shadowing and blocking losses considered are maximum. If we validate this particular day and time simulation for no shadowing and blocking then designed heliostat field is efficient for whole year.

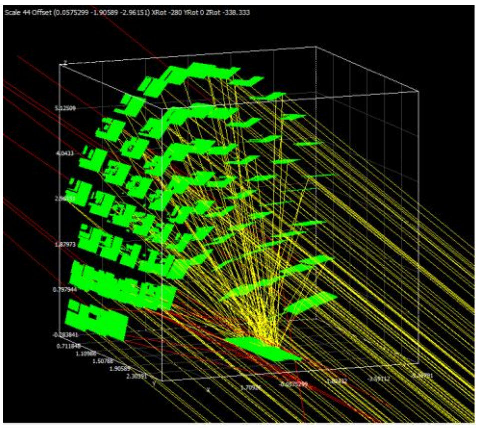


Fig 8. Ray tracing simulation results for different stages in SolTrace

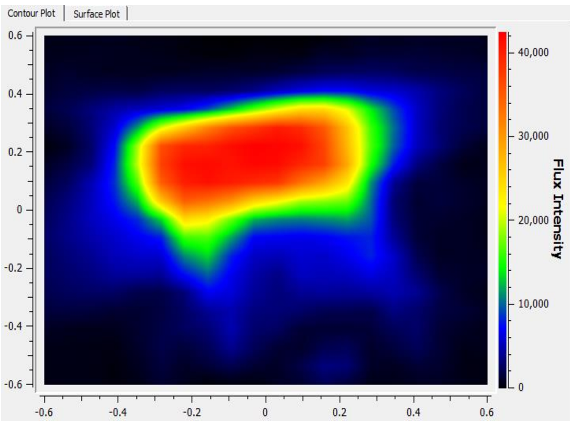


Fig 9 Flux map on receiver in SolTrace

Conclusions

The heliostat field of solar central receiver system designed in this paper is for Pune location (India). From result it is found that heliostat field efficiency is largely depend on cosine efficiency and this efficiency for Pune location lies between70% to 80%.

From heliostat distribution in field, it is clear that heliostats are highly packed near the tower and this density reduces as we go away from the tower.

From SolTrace results it is clear that shadowing and blocking losses are not completely removed and field require some optimization. So this optimization will be the future research scope for this work.

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