
Comparing study of biomimetic spiral and radial staggered layouts of the heliostat field

Maolong Zhang, Xiaoze Du *, Lijun Yang, Chao Xu, Yongping Yang

Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, North China Electric Power University, Beijing 102206, China

Abstract

The radial staggered layout is classical and convenient which has almost been adopted by all the researchers while the biomimetic spiral layout is recommended in recent years, which has some obvious advantages and is promising to be demonstrated in real plant. However, the specific relationship between these two layouts is unknown. In this paper, a detailed compare and analysis of both layouts are introduced. The analysis is mainly concentrating on the circular field, because the large scale and heat storage are more suitable for the circular field that have been an irreversible trend in solar tower power plant. The two kinds of layout are compared from the following three aspects, which are the plant scale, optical efficiency and heliostat field area. Besides the two kinds of layouts, a few of combinations of both layouts are proposed and tested, such as replacing one or some zones of radial staggered field with spiral field, arranging the north field with radial staggered layout while the south part is biomimetic spiral or arranging in turn. The results show that some combination layouts indeed behave better than the original two kinds of layouts.

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Keywords: heliostat field; radial staggered; biomimetic spiral; combinations;

Nomenclature

A gross area of heliostat field, m2

* Corresponding author. Tel.: +86(10)61773918; fax: +86(10)61773877.
E-mail address: duxz@ncepu.edu.cn (X. Du)
1. Introduction

Solar power tower plant (SPT), as one representative technology of concentrating solar power (CSP), has developed rapidly due to its similarity to traditional power plant [1]. One of the dominating performances of SPT is that of the heliostat field, whose expenditure also accounts for the largest proportion of the total investment. On account of its complexity and varieties, the heliostat field attracts lots of attentions from researchers and contributes to explorations of optimizing.

According to local weather and direct normal insolation (DNI), the heliostat field has varieties of layouts, however almost all of them are derived from the radial staggered layout that is firstly proposed in 1970s [2] and has been adopted by the operated commercial plant and numerous optimizing codes, such as RCELL [3], DELSOL [4], HFLD [5], CAMPO [6], NSPOC [7] and so on.

In recent years, as the bionics comes to every domain of our life, the biomimetic spiral layout which originates from the sunflower researched by Vogel [9] and propelled by Jean [10] is recommended because its efficiency is higher and field area is smaller [8].

Since the spiral layout was just put forward, strength and weakness of it and radial staggered layout are still unknown, especially for the circular field. In this paper, comparisons of two kinds of layout and hybrids of both of them are made with different capacities of power plant, the results of which are presented and discussed elaborately to find the best layout.

2. Methods

Because this paper is dealing with an optimization question, the option of the objective function and the approach of calculating the function are very important. What’s more, since this question belongs to non-deterministic polynomial hard questions, intelligent algorithm must be used.
2.1 Objective function

The average annual efficiency of the whole field is selected as the objective function. The representative days of the year are the spring equinox, the summer solstice, the autumn equinox and the winter solstice. Choose 7 time points in one day from dawn to noon. Closer to noon, the time points are denser. The location chosen in this paper is 37°N, where DNI data comes from an existing simulating model [11]. Other relevant parameters for the field in this paper are shown in Table 1.

Table 1. The parameters of the reference heliostat field.

<table>
<thead>
<tr>
<th>Varieties</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Latitude</td>
<td>37.01°N</td>
</tr>
<tr>
<td>Field</td>
<td>Field shape</td>
<td>Circular</td>
</tr>
<tr>
<td></td>
<td>Sun shape, (\sigma_{sun})</td>
<td>2.51 mrad</td>
</tr>
<tr>
<td></td>
<td>Heliostat shape</td>
<td>Rectangle</td>
</tr>
<tr>
<td>Field</td>
<td>Layout way</td>
<td>Radial staggered or others</td>
</tr>
<tr>
<td></td>
<td>Tracing method</td>
<td>Azimuth and zenith ((A_h \text{ and } E_h))</td>
</tr>
<tr>
<td>Heliostat</td>
<td>Heliostat width, (H_w)</td>
<td>12.3 m</td>
</tr>
<tr>
<td></td>
<td>Heliostat height, (H_h)</td>
<td>9.75 m</td>
</tr>
<tr>
<td></td>
<td>Heliostat center height, (h)</td>
<td>5 m</td>
</tr>
<tr>
<td></td>
<td>Beam quality, (\sigma_{bq})</td>
<td>2.74 mrad</td>
</tr>
<tr>
<td></td>
<td>Facet canting</td>
<td>On-axis parabolic</td>
</tr>
<tr>
<td></td>
<td>Receiver shape</td>
<td>Circular</td>
</tr>
<tr>
<td></td>
<td>Target tower receiver height, (H_t)</td>
<td>155 m</td>
</tr>
</tbody>
</table>

2.2 Monte-Carlo ray tracing method

The optical efficiency of the whole field, composed of five terms, is the objective function. The way to calculate the efficiency is the Monte-Carlo ray tracing method that firstly came out in 1977 [12] and has been verified in many codes, such as SCT [13], HFLD [5], CRS4-2 [14]. By use of this classic method, we built our own code for computing the optical efficiency of heliostat field through the Matlab type cell data structure. The computing speed of ray tracing method is slow, therefore the parallel pool in Matlab is adopted.

2.3 Simulated annealing algorithm

Simulated annealing algorithm, first presented in 1953 [15], has been proven by thousands of experiments and rigorous mathematical derivation. Different from the genetic algorithm (GA) which is always early-maturing before gaining the optimal solution and is difficult to enforce the cross of the genic sequence made up by the real number, simulated annealing algorithm makes real number move randomly in neighborhood and it has a so long history that the principle of it is very clear and trustworthy.

3. Field model

No matter for staggered field or for spiral field, the field shape and the parameters waiting to be optimized are unknown until the field models have been confirmed. There are three kinds of field models in our researches that are the staggered field, the spiral field and the hybrid field.
3.1 Staggered field

The radial staggered layout, shown in Fig. 1(a), has been developed after it was firstly presented, there are many ways to generate and optimize this kind of heliostat field such as DELSOL [4], CAMPO [6] and so on. It is convenient for CAMPO to control the size of different zones, hence, the Campo code is opted for generating the staggered field whose optimizing parameters are only the radial space $\Delta r$, between adjacent rows in different zones.

3.2 Spiral field

The biomimetic spiral layout shown in Fig. 1(b), driving from the sunflower, behaves better than the logarithmic spiral and the Archimedean spiral [8], and is generated by the following equations [8, 9]:
\[ r = a \cdot k^b \]  
\[ \theta = 2 \cdot \pi \cdot \phi^{-2} \cdot k \]  

where \( k \) is the \( k^{th} \) heliostat and \( \phi \) is the golden ratio, whose value is \((1+\sqrt{5})/2\). The value of \( \phi \) is also optimized in our researches but the result shows that the golden ratio is the best. The values of \( a \) and \( b \) need to be optimized by the SA algorithm.

### 3.3 Hybrid field

Both of the two kinds of layouts have their characteristics, so the combination of them may be better than themselves. To find the best combination, some simple hybrid field models are built parameters of which need to be optimized are a series of \( \Delta r, a \), and \( b \).

#### 3.3.1 Hybrid field in zones

As known to all, staggered field is usually divided into a few of zones along the radial distance to central tower. Farer is the zone, higher is the optical efficiency. Hence, to research the potential of optimizing every zone, each staggered zone will be replaced by the spiral layout separately, shown in Fig. 1(c). The procedure is described as follows: firstly generating a staggered circular field with some zones and every zone has a radial space, \( \Delta r \), then replace each zone subsequently by the spiral layout with \( a \) and \( b \).

#### 3.3.2 Half staggered layout and half spiral layout

The efficiency of the north field is much better than that of the south field because of the cosine factor even though the blocking and shading factor of the south field is usually higher than that of the north field. In other word, also there may be space that can be optimized in the combination of two kinds of layouts in the north field and south field. The north field can be the spiral layout while the south field is the staggered layout or just arrange the heliostat field in turn, like Fig. 1(d) showing the south spiral and north staggered layout.

### 4. Results and Discussions

The results of comparison in terms of optical efficiency and floor space for different plant capacities will be given in this section. To link the results of the optical efficiency and those of the floor space, the coefficient of used area will also be discussed in this section. For purpose of making the results clarified to observe, all the computing results are shown in two groups, half staggered layout with half spiral layout and hybrid fields in zones and the staggered field and the spiral field are the reference models to be compared with.

#### 4.1 The optical efficiency

Fig. 2(a) and (b) shows the optical efficiency of all the field models. It is obvious that the staggered field is much better than the spiral field in the optical efficiency and nearly all the hybrid fields behave worse than the staggered field except the south spiral and north staggered layout whose efficiency is larger than that of the staggered layout when the plant capacity varies from 50MW to 70MW.

Since the efficiencies of all the layouts change nonlinearly with the capacities, it is hard to get an explicit conclusion. But it can still be seen that in Fig. 2(a), the spiral field and the north spiral and south staggered field are the worst ones not to be suggested and in Fig. 2(b), the optical efficiency of the spiral field in zone 1 is closest to the staggered field when plant capacity is less than 100MW.
4.2 The floor space

As shown in Fig. 3(a), the floor space of the spiral field is the least one and both of the two kinds of half hybrid fields cost more lands than the staggered field, however, in Fig. 3(b), when plant capacity becomes more than 80 MW, the spiral field in zone 3 behave better than the spiral field. It is interesting to find that when the plant capacity is less than 70MW, the difference of all the field models is very small where the conclusion is that if the plant capacity is small, the effect of the layout on the floor space will be very little.

4.3 The coefficient of used area

The line in Fig. 2 is not in accord with the line in Fig. 3 so that we need a new concept to link both of them which is the coefficient of used area, \( \phi \), defined by the following equation:

\[
\phi = \eta / A
\]
where $\eta$ is the optical efficiency of the field and $A$ is the floor space whose unit is km$^2$. The computing results are shown in Fig. 4. In Fig. 4(a), the coefficient of the spiral layout is the largest one followed by the staggered layout. What’s more, in Fig. 4(b), when the plant capacity is beyond 80MW, the coefficient of the spiral layout in zone 3 is better than the spiral layout.

![Graphs showing coefficient of used area](image)

(a) Half staggered layout with half spiral layout  
(b) Hybrid field by zones

**Fig. 4. The coefficient of used area of all the field models**

### 4.4 Research other possible model

From the above, we can conclude that the south spiral and north staggered layout or the staggered layout may be a good choice if we just want to get the maximum efficiency of the heliostat field and the spiral layout or the hybrid field in zone 3 behave better than any other if we want to make the most of the land. Some possible combinations have been omitted which may be superior to the above ones. For example, the south half of zone 3 is spiral layout and all the other parts of the heliostat field are the staggered layout where the zone can also be zone 1 or zone 2.

The results of the researches are shown in Fig. 5. As the figure shows, in terms of efficiency, the staggered field and the south spiral and north staggered field are still the best ones, although the efficiencies of south spiral field in zone 1 and 2 are very close to the previous two models. On the other hand, Fig. 5(b) shows that when the plant capacity is more than 80 MW, both the spiral field in zone 3 and the south spiral in zone 3 are better than the spiral layout while in that capacity range, the spiral field in zone 3 is still the best one.

![Graphs showing optical efficiency and coefficient of used area](image)

(a) The optical efficiency  
(b) The coefficient of used area

**Fig. 5. Comparison of other possible models with the previous best models in terms of the optical efficiency and the coefficient of used area**
5. Concluding remarks

As two kinds of layouts, the staggered layout and the spiral layout, are existing in the modern solar tower power plants, in this paper we discusses the strengths and weaknesses of these two kinds of layouts and research the possible combination of them.

For the circular field, the staggered layout is better than the spiral in the optical efficiency, however, the spiral layout is better than the staggered in the floor space. In the other possible combination layouts, the efficiency of the south spiral and north staggered layout is larger than that of the staggered layout when plant capacity is less than 70MW and the coefficient of used area of the spiral layout in zone 3 is larger than that of the spiral layout when plant capacity is more than 80 MW.

The comparison in this paper may be rough in many aspects, like not considering the effects of tower height and heliostat size, but it can still present many useful suggestions to the layout of the heliostat field. To obtain a more detailed conclusion, there are much work needing to do.

Acknowledgment

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Reference

    Cambridge Studies in Mathematics.