

Optical design of a solar dish concentrator based on hexagonal facets

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A new hexagonal-facet solar concentrator is designed for a satisfactory result in the experimental conditions. The parameters and the positions of the facets are determined by using space geometry and Snell-Descartes law of reflection. The experiment shows the collection efficiency ratio of the solar dish concentrator based on hexagonal facets is enhanced with the increase of the layer number. In consideration of the performance and cost, the optimum model is a 9-layer solar concentrator, which can achieve 82.05% efficiency ratio. This concentrator decreases the cost and simplifies the manufacturing processes, and makes the focal spot more uniform. Compared with paraboloid concentrator, the composition errors have little influence on this new kind of solar concentrator.

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1. Introduction

Renewable source of energy is always being developing to substitute the traditional fossil fuels to meet the needs of industrial development because the environmental pollution and the depletion of energy. Solar energy is a remarkable kind of source of energy because it is inexhaustible. Solar photovoltaic power generation system (CPV) is used widely in solar application. And solar concentrator is the most important component in CPV, which will concentrate the incident sunlight onto a small area. The common method is to design a large dimensional reflective surface when designing a solar concentrator. The collection installation, such as vacuum tube collector will collect the incident sunlight concentrated in the focus point by the large reflective surface.

Actually, it is very common that the solar concentrator will be made of several small reflective surfaces to simplify the manufacturing process and reduce the cost. Joel Herrera et al. [1] discuss a proximate spherical reflective surface composed with numerous hexagonal facets and analysis their spatial position. D. Riveros-Rosas et al. [2] design a spherical solar concentrator which employs several groups of hexagonal facets with different focal lengths, and amend the facets spatial parameters according the incident light.

In the practical application, the reflective surface will usually be designed as paraboloid cause the high

concentration ratio. For an ideal parabolic-reflecting surface, the concentration ration will be limited of 46,000 [3]. Hongcai Ma et al. [4] design a solar dish concentrator based on triangular membrane facets, which achieve 83.63% of radiative collection efficiency. Zhiqiang Liu et al. [5] design a flat-facet solar concentrator with average concentration ratio exceeding 100, which is assembled with numerous quadrilateral facets.

The main barrier to the wide employment of parabolic dish concentrator is the large dimension surface and the non-uniformity of concentrated sunlight although the paraboloid has high concentration ration. The objective of the present research is to design a low-cost concentrator and make the light received in the focal point uniform. We design a solar concentrator composed with numerous hexagons. We use space geometry to analysis the geometric parameters, and the Monte Carlo ray tracing method to verify the performance of the model.

2. Geometric model of the solar

2.1. Paraboloid concentrator

Fig. 1 shows the geometrical model of paraboloid

concentrator. The equation of the paraboloid can be expressed as

$$z = \frac{1}{4f} r^2 = \frac{1}{4f} (x^2 + y^2) \quad (1)$$

According to John A. Dullie [6], the depth h and the edge of angle φ_{rim} of the concentrator can be determined as follows

$$h = \frac{R^2}{4f} \quad (2)$$

$$\varphi_{rim} = \arctan \frac{4fR}{4f^2 - R^2} \quad (3)$$

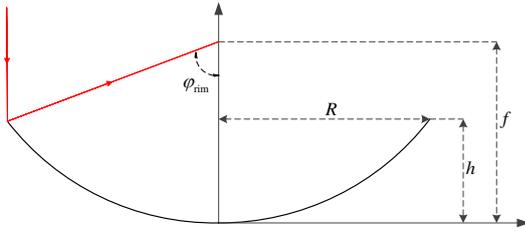


Fig. 1. The geometrical model

2.2. Hexagon-facet concentrator

Based on the paraboloid concentrator, a new kind of solar concentrator which is made of numerous hexagonal facets can be designed in the experimental condition. Fig. 2. shows the top-view of this concentrator. The hexagons colored with grey are the plane mirrors of the same size.

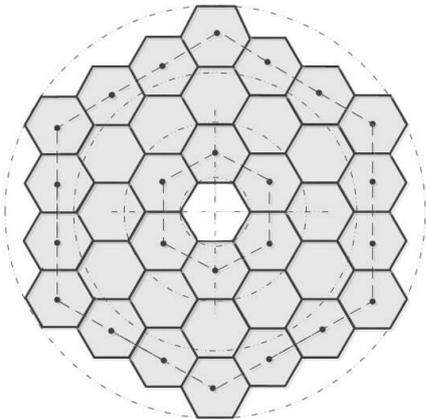
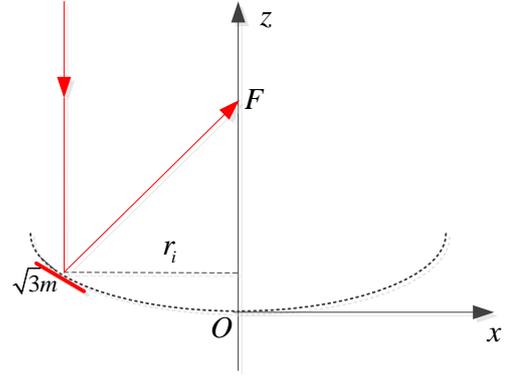
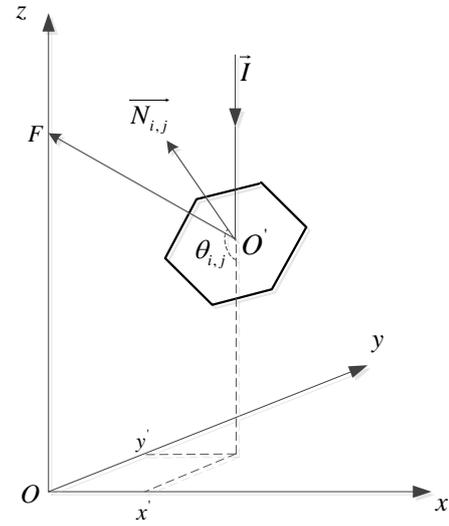


Fig. 2. Hexagon-facet concentrator of 3-layer



(a)



(b)

Fig. 3. (a) The side-view of hexagon-facet concentrator
(b) The position of hexagonal facet (row= i ; column= j)

The side-view of the concentrator is showed in Fig. 3. (a). The red bold line represent the facet located at row j and columns j . The central point of the facet is on the paraboloid. The line connected central point to z -axis is called corresponding radius. The length of the radius is r_i .

For a new kind solar concentrator with M -layer and R -aperture, the number of the facets is

$$N = N_1 + N_2 + \dots + N_i + \dots + N_M = 3M(M + 1) \quad (4)$$

The length of the facet is

$$m = \frac{2R}{\sqrt{3}(2M + 1)} \quad (5)$$

Fig. 3(b) shows the spatial position of hexagonal facet (row = i , columns = j). According to the three dimensions space geometry, we can determine the parameters of the facet. We establish a Cartesian coordinate system in the center of the concentrator. The position of the focal point is

$$F = [0, 0, f] \quad (6)$$

The position of the central point is

$$O' = [x', y', z']_{i,j} \quad (7)$$

Because the central point O' is on the paraboloid,

therefore $(x', y', z')_{i,j}$ satisfies the equation

$$\begin{cases} x'^2 + y'^2 = r_i^2 \\ z' = \frac{1}{4f}(x'^2 + y'^2) = \frac{1}{4f}r_i^2 \end{cases} \quad (8)$$

For the incident ray perpendicular to the facet, in order to direct the reflected light towards the focal plane, according to the Snell-Descartes law of reflection, the incidence vector \vec{l} , the reflection vector \vec{l}' , which is shown as it represent as which is shown in Fig. 3(b), and the normal vector $\vec{N}_{i,j}$ satisfy the equation

$$\vec{N}_{i,j} = \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix}_{i,j} = \frac{\vec{l} - \vec{l}'}{2 \cos \theta_{i,j}} = \begin{bmatrix} N_x = \frac{-x_{i,j}}{2 \cos \theta_{i,j} \sqrt{x_{i,j}^2 + y_{i,j}^2 + (2f - z_{i,j})^2}} \\ N_y = \frac{-y_{i,j}}{2 \cos \theta_{i,j} \sqrt{x_{i,j}^2 + y_{i,j}^2 + (2f - z_{i,j})^2}} \\ N_z = \frac{2f - z_{i,j}}{2 \cos \theta_{i,j} \sqrt{x_{i,j}^2 + y_{i,j}^2 + (2f - z_{i,j})^2}} \end{bmatrix} \quad (9)$$

$\theta_{i,j}$ is the incident angle of the solar ray. According to the spatial geometry relation, it can be expresses as

$$\theta_{i,j} = \frac{1}{2} \arctan \left(\frac{\sqrt{x_{i,j}^2 + y_{i,j}^2}}{f - z_{i,j}} \right) = \frac{1}{2} \arctan \left(\frac{\sqrt{4fz_{i,j}}}{f - z_{i,j}} \right) \quad (10)$$

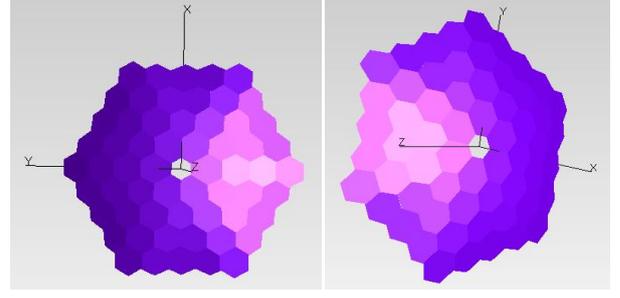


Fig. 4. 4-layer concentrator model

Based on the derivation before, we construct the 3-D model in the simulation software. Fig. 4 shows a 4-layer concentrator model. In the experiment, we will construct some different layer concentrator models, which are similar to the 4-layer concentrator model mentioned above, and validate their performance.

3. Simulation and analysis

We design a hexagonal-facet concentrator considering the practical application. The parameters are showed in Table 1. In order to facilitate the comparison and analysis, the paraboloid concentrator and the hexagonal-facet concentrator both employ the same parameters listed in Table 1. The incident solar flux is 1000 W/m^2 . We construct some new kind concentrator with different layer in the simulation software, and get the results by the simulation.

Table 1. The parameters of the concentrator

Parameter	R / m	f / m	h / m	$\varphi_{rim} / \text{rad}$
				$2\pi / 9$

The parameter k is defined as the ration of the solar radiation received by the new kind concentrator to the radiation received by the paraboloid concentrator. The relationship between the layer number and k is showed in Table 2. As showed in Table 2 with the increase of the number of layers, the value of k will increase, that means the efficiency of solar concentration system will increase, but at the same time we should notice that the length of side will decrease and the total numbers of the facets will increase, which will increase the manufacturing cost. So

in the practical situation, we should adopt different suitable model according to the different actual purposes.

By observing the receiver installed at the focal plane, we notice that the area of the spot received by the new kind concentrator will larger than the spot received by the traditional paraboloid concentrator, and the uniformity of the receiver will be better, as showed in Fig. 5.

Table 2. Simulation value of k

No.	Shape	Length of side/m	Facet number	κ
Case0	paraboloid	/	/	1
Case1	5-layer	0.4721	90	0.8146
Case2	7-layer	0.3373	168	0.8187
Case3	9-layer	0.2623	270	0.8205

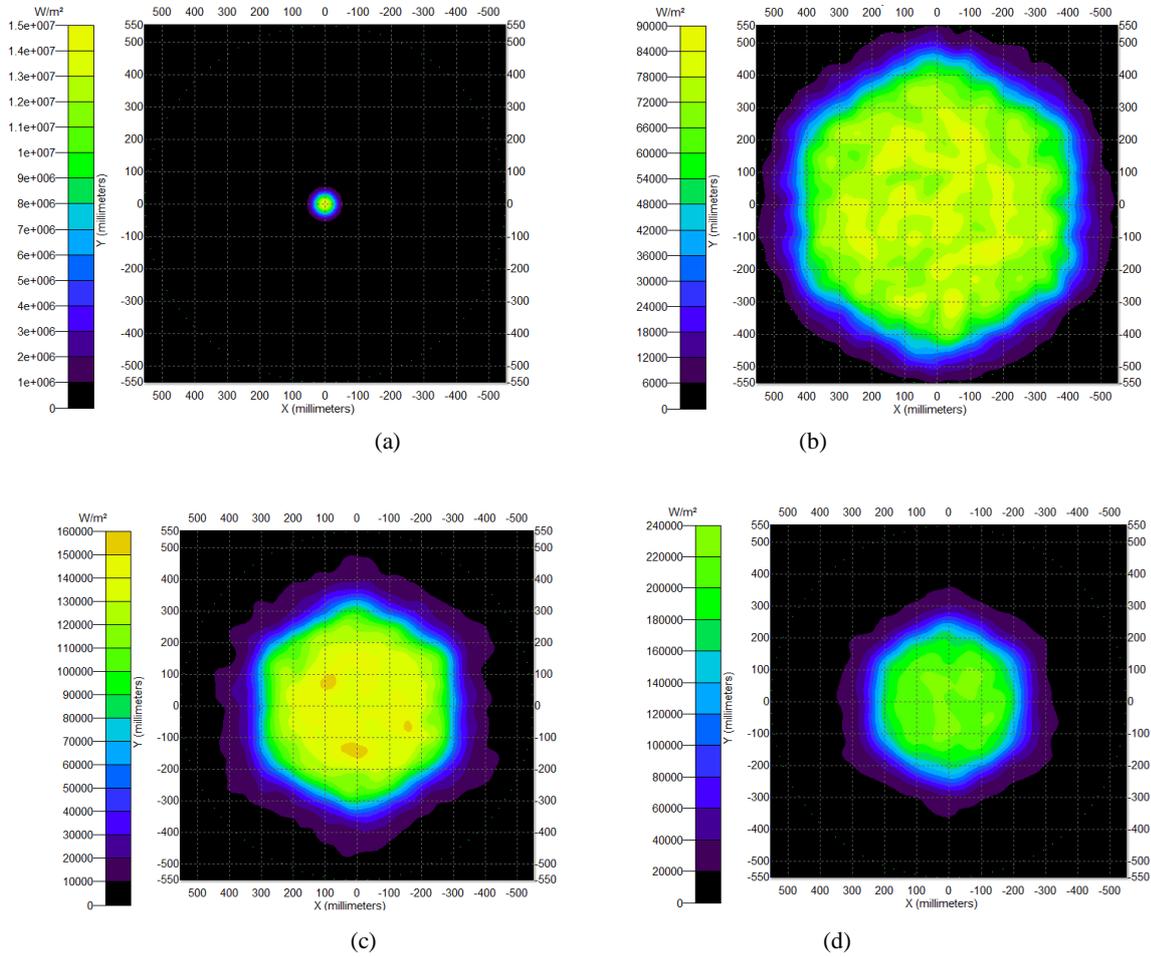


Fig. 5. Uniformity of the receiver: (a) paraboloid (b) 5-layer (c) 7-layer (d) 9-layer

In order to determine the uniformity of focal spot, we statistically analyze the proportion of the energy at the focal plane distributed radially, and map the statistical results into Fig. 6. We find that the spot uniformity of paraboloid concentrator is very poor. Most

of the energy concentrates in the radius of 0.03m range. But the spot uniformity of the new kind concentrator is improved. For a 5-layer concentrator, 96% of the energy distribute in the range of 0.44m radius; for a 7-layer concentrator, 96.8% of the energy distribute in the range

of 0.36m radius; for a 9-layer concentrator, 95.8% of the energy distribute in the range of 0.31m radius.

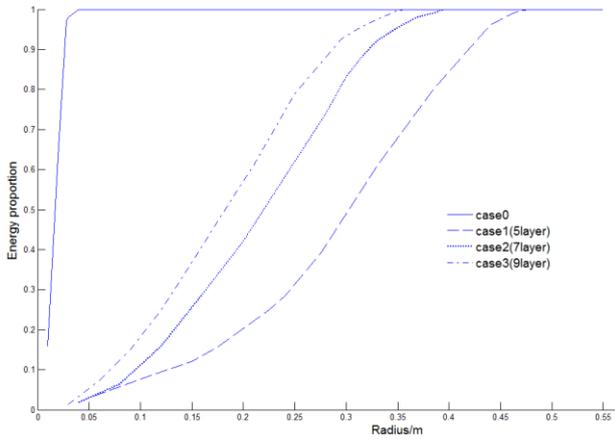


Fig. 6. The energy distribution radially of different solar concentrator

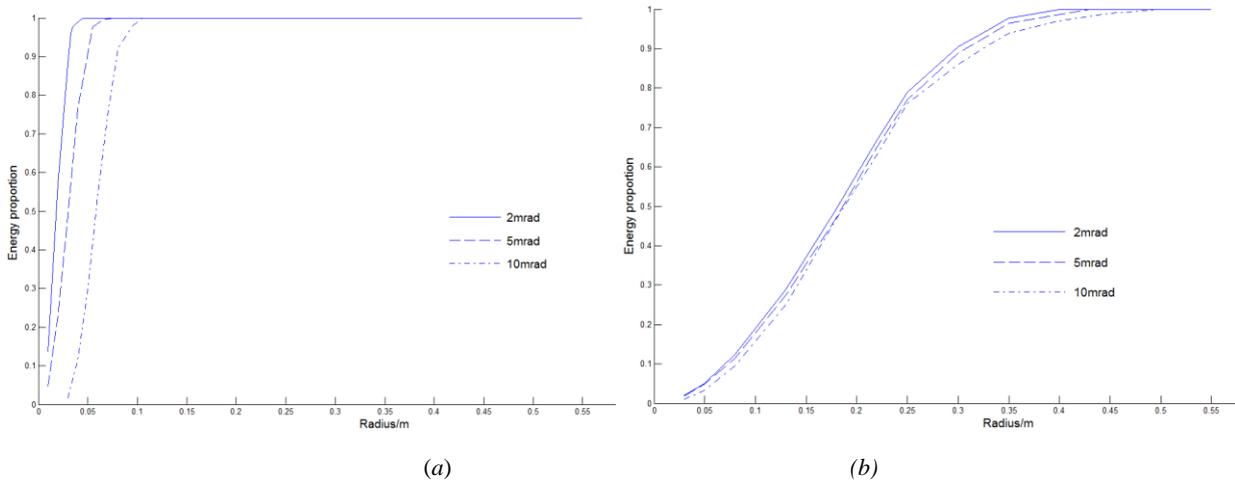


Fig. 7. (a) The energy distribution radially of paraboloid concentrator with different composition error (b) The energy distribution radially of new kind concentrator with different composition error

4. Conclusion

A hexagonal-facet concentrator to replace paraboloid concentrator in the experimental condition is proposed in this paper. The parameters and space positions of the facets are given based on the space geometry and Law of reflection. We conclude that the collection efficiency of the hexagonal-facet concentrator will be enhanced with the increase of the layer number. In consideration of the performance and cost, the optimum model is a 9-layer solar concentrator, which can achieve 82.05% efficiency ratio. This concentrator will decrease the cost because the manufacturing process of the facet is simpler than

Fig. 7 shows the proportion of the energy at the focal plane distributed radially under different composition errors. For a paraboloid concentrator, when the composition error is 2mrad, 96.5% of the energy distribute in the range of 0.033m radius under; 97.7% of the energy is concentrated in the radius of 0.055m range under 5mrad error, and 97.6% of the energy distribute in the radius of 0.095m rang under 10mrad error, compared with 2mrad error, the main area of energy rises by 187.9%. But for the new kind solar concentrator, when the composition error is 2mrad, 96.4% of the energy is concentrated in the range of 0.34m radius, 97.1% of the energy distribute in the radius of 0.37m range under 5mrad error, and 97.5% of the energy distribute in the radius of 0.42m rang, the main area of energy rises merely 23.53%. That means the composition errors have little influence on new kind solar concentrator.

paraboloid. At the same time, compared with paraboloid concentrator, the uniformity of focal spot of this new kind concentrator is improved, and the errors have little influence on it.

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