The design and optimization of concentrating solar system in Wuhan based on clear sky model

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Abstract. To slow down fossil energy usage and protect the environment, concentrating solar power has experienced tremendous growth. This paper focused on the relationship between annual solar irradiation and tilt angle of the concentrating system to find the optimal tilt angle when annual solar irradiation is maximum. In the calculating process, the tilt angle between 0° and 90° is separated from several angles with a 5° interval and calculate the corresponding annual solar irradiation. A relationship line between solar irradiation and tilt angle is indicated, and the optimal tilt angle is discovered. The relationship between solar irradiation and tilt angle in different seasons is also investigated. The result of this paper would be a theoretical foundation to promote the application of concentrating solar systems in Wuhan.

Keywords: Concentrating solar power, solar angle, clear sky model, optimization, annual solar irradiation.

1. Introduction

Energy is an important cornerstone of social and economic development. With the depletion of fossil fuel resources, the increasing population, and the acceleration of urbanization, the development of clean and renewable energy has become a research hotspot to meet the increasing energy demand. Solar energy is currently the largest carbon-neutral energy source available, providing more energy to the earth in an hour than it consumes in a year. Still, solar power currently accounts for only 1 percent of the world's electricity consumption. There are two main types of equipment for solar collection and storage: solar photovoltaics and solar photovoltaics. The former uses solar cells to generate electricity directly based on the principle of the photoelectric effect, while the latter captures solar heat energy for the thermal process of generating electricity [1,2]. There are currently four possible solar concentrating technologies. Firstly, a parabolic trough collector, consisting of a set of reflectors bent in a parabolic shape to focus sunlight onto an absorption tube mounted on a parabolic focus or focal line.

Secondly, the solar tower, also known as the central receiver system, consists of a telescopic field collector that reflects sunlight and concentrates it on a central collector at the top of the tower. Thirdly, the linear Fresnel reflector, which uses rows of slightly curved mirrors to reflect sunlight onto a linear receiver facing down. Fourthly, the parabolic dish system focuses the sun's rays on the focal point above the center of the dish. At present, the medium-sized and large-scale solar concentrator systems are mainly located in Spain and the United States [3].
Chen[4] et al. used numerical methods to study the solar concentrator hot spot generator. Mao et al. [5-7] carried out a preliminary study on solar thermal aggregation and energy storage technology. Castellano et al. [8] designed the optimal arrangement of photovoltaic panel array based on the relationship between solar altitude angle, latitude, and inclination of a photovoltaic panel, to maximize the solar radiation reception of photovoltaic panel array.

It can be seen from the summary of existing literature that the research of solar concentrating systems in the Wuhan area is less and its application is mainly focused on photoelectric conversion, while the solar concentrating system is based on photothermal conversion in the Wuhan area still needs further research. Based on existing literature, this paper mainly considered the characteristics of solar altitude angle and azimuth angle throughout the year in the Wuhan area. And the influence of the inclination angle of the concentrator system on the amount of solar radiation received by the concentrator system is also investigated. The results of this study will provide a theoretical basis for the promotion of the solar concentrator system in the Wuhan area.

2. Physical model and basic parameters
The research object of this paper is the solar concentrator system in Wuhan. The physical model in this paper is shown in Figure 1.

![Figure 1. The solar concentrator with a tilt angle of alpha.](image)

Table 1. Annual definition $K_t$ values in the Wuhan area.

| Month | $K_t$ |
|-------|-------|
| 1     | 0.44  |
| 2     | 0.43  |
| 3     | 0.41  |
| 4     | 0.45  |
| 5     | 0.45  |
| 6     | 0.44  |
| 7     | 0.45  |
| 8     | 0.45  |
| 9     | 0.45  |
| 10    | 0.43  |
| 11    | 0.47  |
| 12    | 0.45  |
The diameter and height of the condensing system are 1000 mm and 500 mm respectively. An adjustable fixing bracket is provided at the bottom of the condensing system. The latitude and longitude of the Wuhan area are 30.5928 °N and 114.3055 °E. Since Wuhan is located in the northern hemisphere, to reach the maximum solar radiation received, the azimuth angle was determined by the compass in the south-due direction of this concentrator. The solar constant \( G_0 = 1367 \text{W/m}^2 \). Based on the clear sky model, the annual clarity \( K_4 \) value in Wuhan is shown in Table 1 [9].

3. Mathematical model
In this paper, the annual solar radiation amount of the concentrator system in Wuhan is calculated by using the clear sky model. The maximum solar radiation amount of the concentrator system is found by selecting different tilt angle values. The mathematical model is as follows:

\[
E_t = E_b R_b + E_{dh} \frac{1 + \cos \alpha}{2} \frac{1}{\rho_g} E_b \frac{1 + \cos \alpha}{2} 
\]  

(1)

where \( \alpha \) is the inclination angle of a solar concentrating system, see in Figure 1, \( \rho_g \) is the surface reflection coefficient.

\[
E_b = K_4 E_{b,0} 
\]

(2)

\[
\frac{E_{dh}}{E_b} = 0.775 + 0.347 \left( \sin \frac{\pi}{2} \right) - \left( 0.505 + 0.261 \left( \frac{1}{2} \right) \cos \frac{2(1-0.9)}{} \right) 
\]

(3)

\[
h_c = \cos^{-1}(-\tan \tan \delta) 
\]

(4)

\[
E_b = E_h - E_{dh} 
\]

(5)

\[
E_{b,0} = \frac{N_{day} \pi}{365} G_{sc} 1 + 0.033 \cos \left( 360^\circ \frac{n-3}{365} \right) \cos \cos \left( \sin h_e - h_e \cos h_e \right) 
\]

(6)

where \( N \) the number of days a month, \( t_{day} \) the seconds in a day, 86,400 seconds per day. \( \delta \) is the sun angle.

\[
\sin \delta = 0.39795 \cos \left[ 0.98563(n-173) \right] 
\]

(7)

\[
h_e = \cos^{-1}(-\tan (1-\alpha) \tan \delta) 
\]

(8)

where \( n \) is the ordinal number of dates throughout the year.

4. Results and discussions
Figure 2 shows the relationship between solar altitude angle and solar azimuth angle throughout the year in Wuhan, with the highest altitude angle in June and the lowest in December.
Figure 2. Annual solar altitude Angle and solar azimuth in the Wuhan area.

Figure 3. Relationship between annual solar radiation and the inclination Angle of the condensing system in the Wuhan area.

Figure 3 shows the annual solar radiation in kW/m². It can be seen from the figure that the annual solar radiation received by the concentrating system reaches the maximum when the tilt angle is equal to 25°.

Figure 4. The relationship between the total solar radiation amount and the inclination Angle of the concentrating system in summer and winter.
Figure 4 shows the relationship between the total solar radiation amount in winter and summer with the change of inclination angle. In this paper, the summer is from April to September, and the winter is from October to March. As can be seen from the figure, in summer, when the inclination angle is 0°, the total radiation reaches its maximum; In winter, the total radiation reaches its maximum at an angle of 50°.

5. Conclusion

Based on the theory of the clear sky model, this paper adopts the numerical analysis method to carry out the optimal design and calculation of the solar concentrating system in Wuhan. The main conclusions are as follows:

1) The solar altitude angle in the Wuhan area its maximum value in June and its minimum value in December.
2) In the due south direction, the inclination angle of 25° can maximize the annual solar radiation received by the concentrating system.
3) For different seasons, the optimal inclination angle to maximize the amount of solar radiation received is different, which is 0° in summer and 50° in winter, which can be solved by installing adjustable supports.

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References

[1] Barlev, D., Vidu, R., & Stroeve, P. (2011). Innovation in concentrated solar power. Solar energy materials and solar cells, 95(10), 2703-2725.
[2] Banos, R., Manzano-Agugliaro, F., Montoya, F. G., Gil, C., Alcayde, A., & Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy: A review. Renewable and sustainable energy reviews, 15(4), 1753-1766.
[3] Zhang, H. L., Baeyens, J., Degrève, J., & Cacè res, G. (2013). Concentrated solar power plants: Review and design methodology. Renewable and sustainable energy reviews, 22, 466-481.
[4] Chen, W. H., Wang, C. C., Hung, C. I., Yang, C. C., & Juang, R. C. (2014). Modeling and simulation for the design of thermal-concentrated solar thermoelectric generator. Energy, 64, 287-297.
[5] Mao Q, Yuan Y, Shuai Y. Effects of atmospheric aerosol on the direct normal irradiance on the earth’s surface [J]. International Journal of Hydrogen Energy 2014; 39:6364-6370.
[6] Mao Q, Shuai Y, Yuan Y. Study on radiation flux of the receiver with a parabolic solar concentrator system [J]. Energy Conversion and Management 2014; 84: 1-6.
[7] Mao Q. Recent developments in geometrical configurations of thermal energy storage for concentrating solar power plant[J]. Renewable & Sustainable Energy Reviews 2016; 59: 320-327.
[8] Castellano, N. N., Parra, J. A. G., Valls-Guirado, J., & Manzano-Agugliaro, F. (2015). Optimal displacement of photovoltaic array’s rows using a novel shading model. Applied Energy, 144, 1-9.
[9] https://www.gaisma.com/en/location/wuhan.html