# Performance investigation of a concentrating photovoltaic/thermal system with transmissive Fresnel solar concentrator

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## ARTICLE INFO

## ABSTRACT

A design method of a cycloidal transmissive Fresnel solar concentrator which can provide a certain width focal line was presented in this study. Based on the optical principle of refraction, the dimensions of each wedge-shaped element of Fresnel lens are calculated. An optical simulation has been done to obtain the optical efficiency of the concentrator for different tracking error and axial incidence angle. It has been found that about 80% of the incident sunlight can still be gathered by the absorber when the tracking error is within 0.7°. When the axial angle of incidence is within 10°, it almost has no influence to the receiving rate. The concentrating photovoltaic/thermal system with transmissive Fresnel solar concentrator has been designed in this paper. Take the gallium arsenide high concentrated battery as the receiver, experimental research about cylindrical Fresnel concentrating photovoltaic/thermal system is undertaken in the real sky. Main parameters are tested such as the temperature distribution on receiver, electric energy and thermal energy outputs of concentrating photovoltaic/thermal system, the efficiency of multipurpose utilization of electric and heat, and so on. The test results in clear weather show that maximum electric generating efficiency is about 18% at noon, the maximum heat receiving rate of cooling water is about 45%. At noon time (11:00–13:00), the total efficiency of thermal and electricity can reach more than 55%. Performance of this concentrating photovoltaic/thermal system with transmissive Fresnel solar concentrator is studied and compared in two types typical weather, hazy weather and clear weather, it can be known from results that hazy weather has great influence to electric generation efficiency but it has less effect to heat efficiency of cooling water.

## 1. Introduction

Fresnel lens has many advantages such as simple structure, low cost, ease for manufacturing and mass production [1], and been widely used in concentrating photovoltaic systems. For example, Wu et al. [2] researched the characteristic of a 0.6 mm thick aluminium trough wall Fresnel lens PV Concentrator at different solar radiation intensities; Xie et al. [3] studied and compared the performance of a line-focus Fresnel lens solar collector using different cavity receivers.

Fresnel lens was invented in 1822 by a French mathematician and physicist, Augustin Jean Fresnel [4]. In 1970s, NASA made some detailed description about design method and transmittance of Fresnel lens, it guides researchers to the right direction. Generally, base surface of Fresnel lens is flat for easy manufacturing. A

large amount of investigations about flat Fresnel lens have been done by researchers [5,6]. Yeh and Yeh [7] provided the information of illumination patterns under a circular lens, which will help to match up various spectrum distributions to their suitable solar applications. Nia et al. [8] used flat Fresnel lens and thermoelectric module to concentrate solar beam and generate electrical power, the output power can reach 1.08 W with 51.33% efficiency under radiation intensity of 705.9 W/m$^2$. For the polygonal shapes flat Fresnel lens, Neo et al. [9] presented an automated 4-axis ultra-precision machining technique for manufacturing an array of hexagonal Fresnel lenses, it can reduce the cost of manufacture. Widest possible acceptance angles, higher tolerances both in manufacturing and operation, less precise tracking, misalignment compensation are the parameters of non-imaging optics which makes it most efficient and best suitable for concentrated solar power technology [4]. He et al. [10] did some research about a thermoelectric cooling and heating system driven by a heat pipe photovoltaic/thermal (PV/T) panel. The results shown that the

average coefficient of performance (COP) of thermoelectric module of this system can be about 1.7, the electrical efficiency of the PV/T panel can reach 16.7%, and the thermal efficiency of this system can reach 23.5%. In order to improve the quality control of Fresnel lenses in scenarios of high volume production, Herrero et al. [11] presented a simple method called "checkerboard method" is presented.

With the advances in the manufacturing process, curved surface Fresnel lens can be realized. For the concentrator systems, curved surface Fresnel lens has more advantage than the flat one [12,13]. Thus, in recent years, many research about curved surface Fresnel lens have been done. In order to improve the optical efficiency and uniformity of light spot, Gonzlez [14] designed a curved surface Fresnel lens with line focus. Yeh [15] did a study about an elliptical-based Fresnel lens concentrator system using optical geometry and ray tracing technique, this study identifies that the optimum performance that occurs at the lenses with the focal ratio falls between 0.4 and 0.55. Miller and Kurtz [16] did a research about wavelength-specific optical performance of concentrated photovoltaic (CPV) systems, for refractive optical components, the sunlight transmittance for standard PMMA is about 92%. Ryu et al. [17] designed a novel Fresnel lens and successfully solved the problem about un-uniform light intensity distribution on focus. Cui et al. [18] analyzed the optical performance of the Fresnel lens by the ray tracing method. In his study, the transmission efficiency and the dispersion spot deviation of the Fresnel lens with different relative aperture were figured out and compared for incidence angle changes from 0° to 6°. Montes et al. [19] designed and evaluated different achromatic Fresnel lens solutions capable of operating as concentrators aimed at photovoltaic cells systems. It is found that chromatic dispersion is minimized and the efficiency rate is over 85% of efficiency for a wide spectral range (from 350 nm to 1100 nm). Pan and Huang [20] has designed a new kind of Fresnel lens which can increase the uniformity a lot and keep the acceptance angle within solar angle without second optical element and complicated theoretical approaches. It yields not only uniform concentration but also a high concentration ratio. Hui et al. [21] built an one dimensional steady heat transfer model of solar photovoltaic/thermal system. The thermal, electricity and exergy efficiency of six different structures were calculated and compared. Han et al. [22] presented a two-stage Fresnel lens with modular device and investigated its performance. Based on the analysis of rays passing through the wedge structure of the lens, the optical efficiency is obtained under different incidental angles. Zheng et al. [23] constructed a prototype cylindrical compound Fresnel concentrator and tested the solar energy use efficiency by vacuum tube to investigate its characteristics.

In addition, characteristics and performance of solar cells under high intensity have been studied in a large amount of investigations [24–26], it is helpful to the research about PV cell application in the PVT system.

Concentrating photovoltaic/thermal (CPV/T) system with transmissive Fresnel solar concentrator is designed in this paper. Take the gallium arsenide high concentrated photovoltaic cell as the receiver, experimental research about cylindrical compound Fresnel CPV/T system is undertaken in the real sky. Main parameters are tested such as the temperature distribution on receiver, electric energy and thermal energy outputs of CPV/T system, the rate of multipurpose utilization of electric and heat, and so on.

## 2. Design method

The Fresnel lens with cycloidal outside surface have better capacity to resist climate factors and protect interior structure. The gravity center of Fresnel lens with cycloidal outside surface can be designed near to the axial and it can decreases the power consumption of tracking system. The working principle of this Fresnel lens can be described in Fig. 1, and ignoring sun shape angle and considering the incidence sunlight parallel to the symmetry line of the cycloidal Fresnel lens.

In order to simplify the design method, we should make some assumptions as follow:

(1) The thickest points of each wedge in concentrator are in the same circle, it is inner circle in Fig. 1, and each thinnest point is in the middle circle analogous.

(2) In the design process, light concentrate condition was considered only about the middle point of each wedge, if the middle points of wedge have good concentrating performance, it is believed that the whole wedge is well designed.

(3) Compare with the distance between incidence point and collector, the thickness of wedge is very small and can be neglected.

From Fig. 1 that the outside circle equation is:

$$x^2 + y^2 = r^2 \tag{1}$$

If neglecting the thickness of a wedge, one can get such geometrical relationship:

$$\text{tg}\beta \approx \frac{x}{r+y} = \frac{x}{r+\sqrt{r^2-x^2}} \tag{2}$$

where $x$ and $y$ are the coordinates of the incident point.

Bottom straight line of wedge is CD, its equation is: $y = k_{CD}x + b$, where $k_{CD} = \text{tg}\gamma$.

For the point $A(x_i, y_i)$, we can get the relationship that: $\text{tg}\beta_i = \frac{x_i}{r+y_i}$, $\beta_i$ is the angle between straight line AC and axial $y$. Similarly, the angle between straight line ED and axial $y$ is $\beta_{i+1}$, $\text{tg}\beta_{i+1} = \frac{x_{i+1}}{r+y_{i+1}}$.

Next step is to get the angle $\gamma_i$, if we get it, the shape of wedge $i$ can be determined.

Equation of $\overline{ABC}$ is: $y = \frac{r+y_i}{x_i} \cdot x - r$, so the coordinate of point B can be calculated as:

$$x_B = \frac{k_i r - \sqrt{k_i^2 r^2 - (1+k_i^2)(2rd-d^2)}}{1+k_i^2} \tag{3}$$

$$y_B = k_i x_B - r$$

$$k_i = \frac{r+y_i}{x_i}$$

Similarly, the coordinate of point C can be calculated as:

$$x_C = \frac{k_i r - \sqrt{k_i^2 r^2 - (1+k_i^2)(2rl-l^2)}}{1+k_i^2} \tag{4}$$

$$y_C = k_i x_C - r$$

Form Eq. (1), it can be get the $\beta$:

$$\beta = \text{arctg}\frac{x}{r+\sqrt{r^2-x^2}} \tag{5}$$

As a matter of fact, it can be known from Fig. 1 that the refractive index is:

$$n = \frac{\sin(\beta+\gamma)}{\sin(\alpha+\gamma)} \tag{6}$$

where $n$ is refractive index, $\alpha+\gamma$ and $\beta+\gamma$ is the incidence and refraction angles on the lower side of wedge, respectively. When