Optical Analysis and Optimization of the Linear Fresnel Collector's Mirror Field

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Abstract: The optical losses of the Fresnel collector's mirror field are analyzed mathematically and optimization for the design parameters is made. In analysis of the optical characteristics, the optical losses of different segment are described according to the optical principles. And the optical efficiency is derived from the losses description. Finally, the influences brought on by the mirror field parameters, such as the height of the receiver, the width of the mirror and the interval between adjacent mirrors, are showed up respectively so as to guide the optimal design.

Introduction

The linear Fresnel reflective collector is made up of reflector and radiation absorber. The reflector is consisted of a series of plane mirrors that reflect incident light to the fixed cavity absorber. The absorber heats the working fluid flowing within the tubes after absorption of the focused solar radiation energy and the temperature is usually up to 100 ℃ ~ 300 ℃ [1].

In the design of LFR(linear Fresnel reflector), the emphasis is lay on the shading and blocking phenomenon between adjacent mirrors. The mirror's width and the interval between two mirrors next to each other should be determined carefully. In the areas of middle and high latitude, the length of the cavity absorber need to increase because of offset of the facula.

This article describes the optical losses of LFR and tells the method to calculate the optical efficiency. On the assumption that the number of mirrors in the mirror field is constant, the relations between the optical efficiency and the parameters of the collector are revealed. Meanwhile, the optimal design of the collector is carried out.

Optical Loss Analysis

There are many factors that affect the optical efficiency of the collector, including incidence angle of light, shading and blocking between adjacent mirrors, the offset of the facula, the optical properties of different surfaces, etc. Among them, the influence brought by the geometry factors is more evident, which are describe as follows.

Incidence angle

Number each mirror of the LFR as 1,2,…,N, and then the equivalent area perpendicular to the incident light is illustrated in Fig. 1. According to the geometrical optics rules, the area can be described as follows:

$$A_p = L \cdot W \cdot \sum_{n=1}^{N} \cos q_n \tag{1}$$

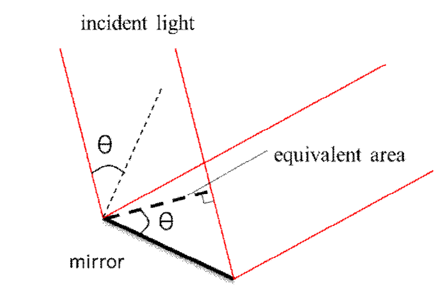


Fig.1 Schematic of end loss

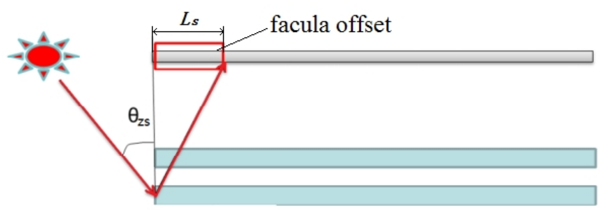


Fig.2 Cosine effect of incident ray

For each mirror, if the incident angle of light is 0, the energy falling on the mirror reaches its peak value. When the incident angle isn't equal to 0, the incident energy is $\cos q$ times more than the peak value. In fact, there's no chance that the light is perpendicular to the mirror no matter how much the incident angle is. Therefore, the cosine loss is inevitable.

Offset of the facula

If the length L of the absorber is larger than the length of the mirror, the facula caused by the reflected light from the mirror field will skew along the longitudinal direction resulting in the off-target of the concentrated light partially (Fig.2). The offset distance L_s can be calculated as follows,

$$L_s = f \tan q_{zs} \tag{2}$$

The energy that falls out of the absorber and are not absorbed is known as the end loss.

Shading and blocking

When the sunlight's incident angle is small, the shading and blocking phenomenon would occur between adjacent mirrors. The loss of the light that doesn't fulfill the mirrors is called shading loss (Fig.3), and that is blocked by the back of the mirrors is called blocking loss (Fig.4). Due to the symmetry of the mirror field, it's totally convenient to analyze the shading and blocking loss only in the incidence angle range of 0 ~ 90 °.

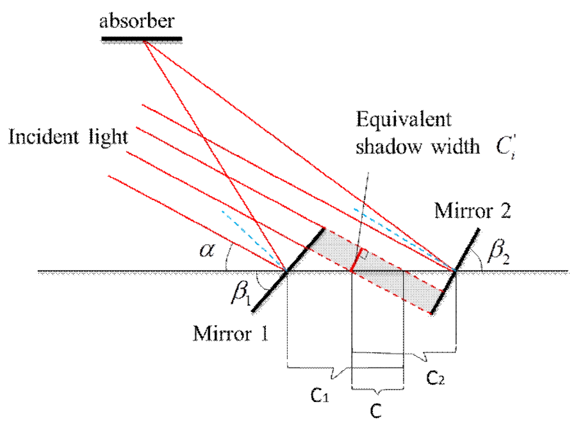


Fig. 3 Schematic of the shading loss

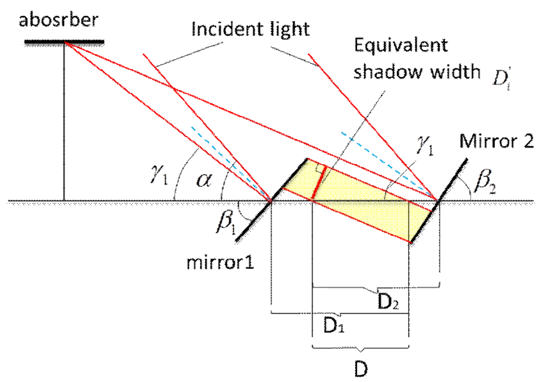


Fig.4 Schematic of the blocking loss

Since either, neither or both of the shading and the blocking may exist between two adjacent mirrors, the effective light receiving area of the mirror field is showed as follows:

$$A_u = A_p - L \cdot \sum_{i=-n}^{n} \max\{C_i', D_i', 0\} \tag{3}$$

Shadows of the support and absorber

The cavity absorber in this case is a semicircular trough shape, the height of which is larger than the width of the mirror field. When the slant incident of the sunlight is greater than 40°, the shadow of the absorber will fall on the mirror field, causing the incident solar radiation energy loss. The collector is located in Guangzhou of south China where the latitude is low, so the facula offset in north-south direction can be ignored. Along the direction of the incident light, the absorber's shadow projected on the mirrors is calculated as follows:

$$A_{receiver} = \frac{d}{2}(1+\sin a)\cdot L \tag{4}$$

As for the support of the collector, the shadow's area $A_{support}$ is small so that it can be estimated according to the actual situation.

Optical efficiency calculation

The optical losses mentioned above have essential impact on the total optical efficiency of the Fresnel collector. If we pay attention to the single energy loss to quantify the influence, relative efficiencies are put forward. Table 1 shows the formula of the unique efficiencies.

Table 1 The optical efficiencies come of the single factor

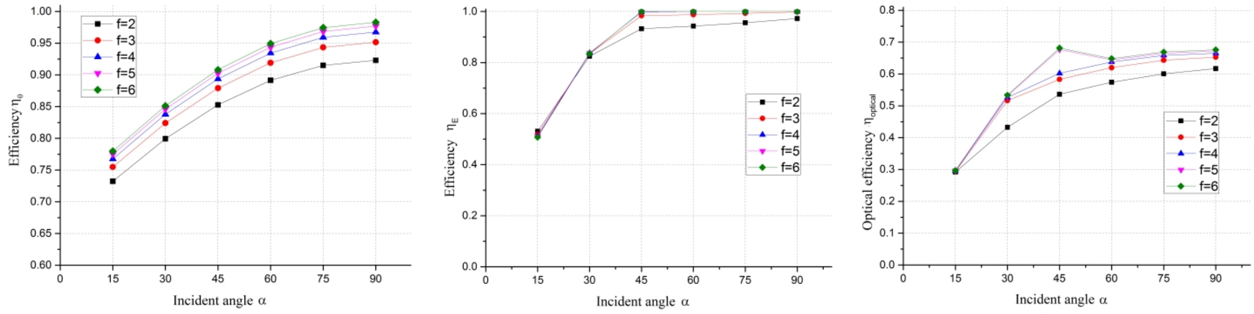
Efficiency	*Formula*
Cosine efficiency	$h_q = \frac{A_p}{A}$;
Shading efficiency	$h_E = \frac{A_u}{A_p}$;
End efficiency	$h_{end} = 1 - \frac{f}{L}\cdot\frac{\cos g_s}{\tan a_s}$;
Support efficiency	$h_{support} = \frac{A_u - A_{receiver} - A_{support}}{A_u}$;
Optical efficiency	$h_{optical} = \frac{Q_u}{AI_b} = h_q \cdot h_E \cdot h_{end} \cdot h_{prop} \cdot h_{support} \cdot h_{trace}$

Where h_{prop} is the product of the reflectivity of the material r_m (set as 0.935), the transmittance of the transparent cover t_r (set as 0.91) and the absorption rate of cavity's inner wall a_r (set as 0.9), that is $h_{prop} = r_m \cdot t_r \cdot a_r$; h_{trace} is the efficiency come of the tracking error caused by the tracking system of the mirrors.

Optimal Design

When designing the collector's mirror field, a set of appropriate design parameters contribute to a high optical efficiency. When the number of the mirrors is fixed, the height of the absorber f, the horizontal interval S between adjacent mirrors and the width of the mirror W are the main factors affecting the optical efficiency of the collector.

Height of the absorber

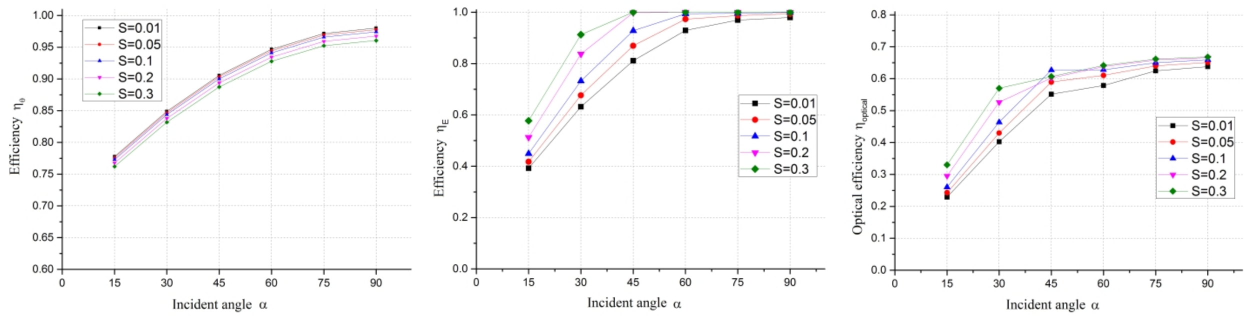


(a) (b) (c)

Fig. 5 Relation between the optical efficiency and receiver's height

Seen from Fig.5, the height of the absorber has an obvious effect on all the optical efficiencies when it is smaller than 3m, but slight effect when greater than 3m. The effect caused by the absorber's shadow is becoming small with the height rising. In Fig.5(c), there's a low ebb on the curves of f=5 and f=6 at $a = 60°$, because from the incident angle on, the absorber's shadow falls on the mirrors.

Interval between adjacent mirrors

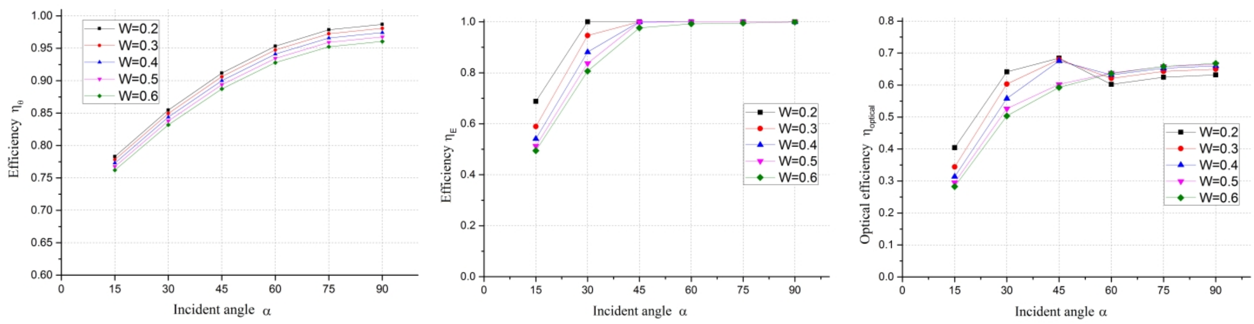


(a) (b) (c)

Fig. 6 Relation between the optical efficiency and adjacent mirrors' interval

From Fig.6, we know that the interval S barely has effect on the efficiency h_q, but has a serious effect on h_E, which increases rapidly with the interval rising. Fig.6(c) shows the optical efficiency increases when the interval becomes larger.

Width of the mirror



(a) (b) (c)

Fig. 7 Relation between the optical efficiency and mirror's width

Seen from Fig. 7(a)(b), the width of the mirror effect the efficiency h_q slightly and has a huge effect on h_E, for it decrease rapidly with the rise of the width of mirror. This indicates the shading and blocking is a very important problem for consideration. And Fig.7(c) shows that the narrow mirrors greatly impact the optical efficiency of the collector. When the slant incident angle of the sunlight is smaller than 55°where the shadow of the absorber is out of the mirror field, the optical efficiency drops with the width rising. But it begins to crease when the incident angle is greater than 55°where the absorber's shadow is on the mirrors.

Summary

From the analysis above, we know that the optical energy losses dominantly effect the optical efficiency of the Fresnel collector. The cosine loss and the shading-blocking loss both appears significant but the latter is easy to vary greatly with the design parameters such as the height of the absorber, the width of the mirror and the interval between mirrors. Also the incident angle of sunlight would greatly effect the total optical efficiency when it is small, which means the collector performs well at the noon. On the basis of the results, we can choose the appropriate parameters for the design of the linear Fresnel solar collector.

References

[1] D.R.Mills. Project Proposal for a Compact Linear Fresnel Reflector Solar thermal Plant in the Hunter Valley[EB].

[2] Zhang Liying. Thermal analysis of cavity absorber for solar energy heat collector[J]. Journal of engineering thermophysics, 2008, 29(9).

[3] Zhai Hui. Theoretical and experimental investigation of linear concentrating solar collector with cavity absorber[D]. Shanghai: Shanghai Jiao Tong University, 2009.

[4] Bai Tao. Analysis on heat removal factor for cavity absorber of a linear solar concentrator and its utilization[D]. Shanghai: Shanghai Jiao Tong University, 2010.

[5] John A. Duffie, William A. Beckman. Solar Engineering of Thermal Processes[M]. New Jersey: John Wiley & Sons, Inc., Hoboken. 2013.

