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ANALYSIS OF PARAMETERS OF LINEAR FRESNEL REFLECTOR SOLAR ENERGY CONCENTRATOR

The optical efficiency and concentration rate of linear Fresnel reflector solar concentrator are investigated. The mathematical model and a simulation program are developed. The dependences of optical efficiency and concentration rate on different parameters are investigated. It is shown that during the design of linear Fresnel reflector concentrators the focal distance can be increased, and to obtain the required optical efficiency and concentration rate, the mirror width and the distance between the mirrors must be optimized.

Keywords: linear Fresnel concentrator, solar, mirror, optical efficiency, concentration rate, focus, reflector.

Introduction. Concentrating solar power is one of several preferred methods of solar energy using. Different types of point focus and linear focus concentrators are developed. Linear Fresnel Reflector Solar Concentrators (LFRSC) have several advantages in comparison with parabolic trough systems [1, 2]. Linear Fresnel mirror reflecting concentrators capture the sun's energy with flat mirrors that reflect and focus the sunlight onto a fixed linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to heat a traditional power cycle that spins a turbine that drives a generator to produce electricity. Linear Fresnel mirror reflecting concentrators consist of a large number of mirrors in parallel rows that are typically aligned in a north-south direction to maximize the annual and summer energy collection. With a single-axis sun-tracking system, this configuration enables the mirrors to track the sun from east to west during the day, which ensures that the sun reflects continuously onto the receiver tubes. These types of concentrators are used generally in the solar field for electricity generation.

In comparison with parabolic trough mirror reflecting concentrators, the optical losses in LFRSC are more due to the shading and blocking effects of neighboring mirrors. Therefore, the optical efficiency of LFRSC or the thermal energy production generally is analyzed depending on different parameters [1-4]. Fewer investigations are devoted to the analysis of another important parameter - the concentration rate of LFRSC. The analysis of concentration ratio is significant not only for thermal energy generating systems, but also for concentrating photovoltaic systems (CPV) which are predicted to have an important role in future solar energy systems [5].

In this paper, a full analysis of a linear Fresnel mirror reflecting concentrator is conducted and the dependence of both optical efficiency and concentration ratio on different parameters is investigated.

Modelling of a linear Fresnel reflector solar concentrator. LFRSC consists of flat mirrors and a linear receiver placed on the focal area. Each mirror is reflecting the incident solar rays onto the receiver (Fig. 1). The width of the mirrors, and the distance between the mirrors are constant values. The receiver is fixed and the mirrors are tracking the sun during the day.

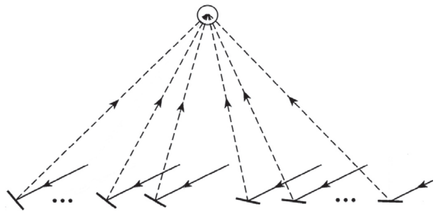


Fig. 1. Linear Fresnel reflector solar concentrator

In Fig. 2, the half of the LFRSC is presented for simplicity.

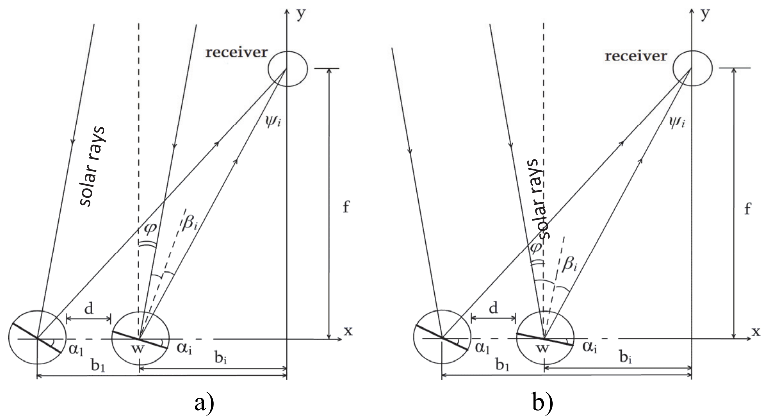


Fig. 2. The structure of linear Fresnel mirror reflectors
The angle between the incident rays and the horizontal axis is acute (a) and obtuse (b)

The position of the first mirror center is (the mirrors are enumerated from left to right):

$$b_1 = -0.5 * [(n-1) * (w+d)],$$

where n is the total number of mirrors, w is the mirror's width; d is the distance between the two neighboring mirrors. The second mirror center position will be:

$$b_2 = b_1 + (w+d).$$

In this way, the position of each mirror's center can be calculated as:

$$b_i = b_{i-1} + w + d, \quad (1)$$

where i is the mirrors' number, b_{i-1} - the position of the previous mirror's center. Note that if the mirrors' number is odd the middle mirror center lies on axis **y**, and if the mirrors' number is even, axis **y** passes between the two central mirrors.

To calculate the inclination angle α of each mirror, let as consider the following two cases.

1) The angle between the incident rays and the horizontal x axis is acute (Fig. 2a):

$$\begin{cases} \alpha_i = \beta_i + \varphi \\ \alpha_i = \psi_i - \beta_i \end{cases} \Rightarrow 2\alpha_i = \psi_i + \varphi \Rightarrow \alpha_i = \frac{1}{2}(arctg(\frac{b_i}{f}) + \varphi).$$

2) The angle between the incident rays and the horizontal x axis is obtuse (Fig. 2b):

$$\begin{cases} \alpha_i = \beta_i - \varphi \\ \alpha_i = \psi_i - \beta_i \end{cases} \Rightarrow 2\alpha_i = \psi_i - \varphi \Rightarrow \alpha_i = \frac{1}{2}(arctg\left(\frac{b_i}{f}\right) - \varphi).$$

By combination of the two formulae presented above, for α we shall have:

$$\alpha_i = \frac{1}{2}[arctg\left(\frac{b_i}{f}\right) \pm \varphi]. \quad (2)$$

Thus, having the total number of mirrors, the width, the distance between the mirrors, the focal distance and the incident angle of solar rays, the position and inclination angle for each mirror can be defined by formulae (1) and (2). Note that φ is the transversal angle, and the longitudinal angle is not considered.

The optical efficiency of LFRSC is the ratio of the sum of effective reflected beams on the receiver and the aperture of the concentrator. It can be presented as follows:

$$e = \frac{\sum_{i=1}^{n} t_i}{(2b_1 + w)}, \quad (3)$$

where t_i is the effective reflected beam width from i – th mirror. Note that, as the effective reflected beam is assumed the beam which reaches the receiver.

The effective reflected beam width depends on all parameters of LFRSC and it can be changed due to the shading and blocking effects of the neighboring mirrors (Fig. 3).

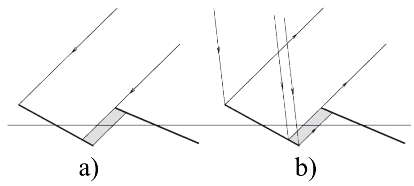


Fig. 3. Optical losses in the system: a - shading, b - blocking

The effective reflected beam width depends also on the receiver width and the eflected beam width. To determine the effective reflected beam width let's consider the following four possible cases presented in Fig. 4.

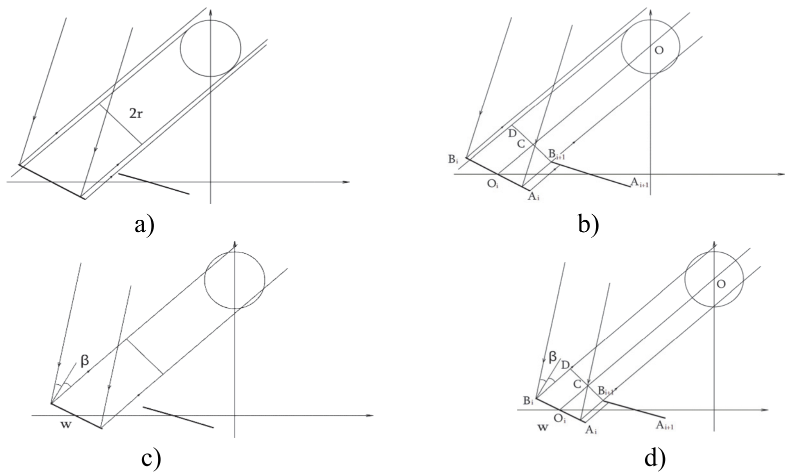


Fig. 4. The reflected beam on the receiver surface. The reflected beam width is: a - greater than the receiver diameter; b - greater than the receiver diameter and there are shading or blocking losses, c - smaller than the diameter of the receiver, d - smaller than the diameter of the receiver and there are shading or blocking losses

Case Fig. 4a). The width of the reflected beam is greater than the receiver width, part of the reflected beam passes near the receiver, and there is no shading or blocking effect. In this case the effective reflective beam width is equal to the width of the receiver:

$$t_i = 2 * r.$$

Case Fig. 4b). The width of the reflected beam is greater than the receiver width, part of the reflected beam passes near the receiver, and there are additional optical losses due to shading or blocking. In this case, the effective reflective beam width is calculated by the following equation:

$$t_i = B_{i+1}C + CD,$$

where $B_{i+1}C$ is the distance of point B_{i+1} from line O_iO, and CD =*r*.

Case Fig. 4c). The width of the reflected beam is smaller than the receiver diameter, the reflected beam fully reaches the receiver, and there is no shading or blocking effect. Thus the effective reflective beam width equals the reflected beam width:

$$t_i = w * cos\beta,$$

where β is the half of the angle between the incident and reflected rays, and the mirror's width.

Case Fig. 4d). The width of the reflected beam is smaller than the receiver diameter, and there are additional optical losses due to shading or blocking. The effective reflected beam width can be calculated as follows:

$$t_i = B_{i+1}C + CD,$$

where $B_{i+1}C$ is the distance of point B_{i+1} from line O_iO, and CD is calculated as:

$$CD = \frac{w}{2} * cos\beta.$$

Having the coordinates of points $O(0; f)$ and $O_i(b_i; 0)$, we can get the equation of line O_iO. The coordinates of point B will be

$$(b_{i+1} + \frac{w}{2} cos\alpha_{i+1}; \frac{w}{2} sin\alpha_{i+1}),$$

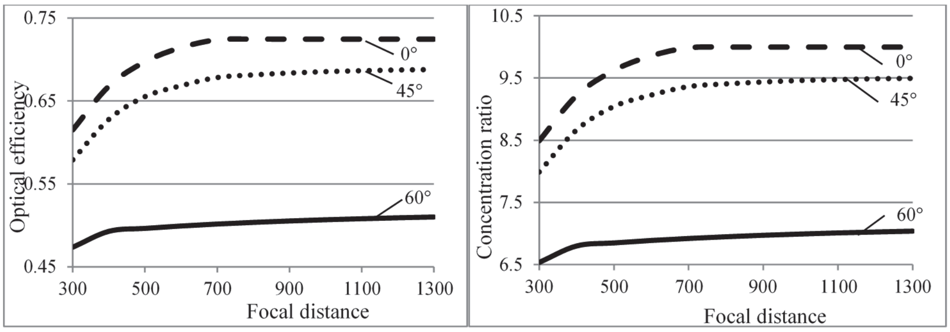
where b_{i+1} is the mirror center distance from the axis **y** calculated by equation (1) and α_{i+1} is the angle between the mirror and axis **x** calculated by equation (2). Using the formula of linear geometry for the distance from a point to a line, we can calculate the distance $B_{i+1}C$. In particular, when point B_{i+1} lies above the line O_iO, the distance $B_{i+1}C$ will have a negative sign. Generally, the concentration rate is determined as the ratio of the aperture area of the concentrator to the receiver area. For LFRSC, the concentration rate is determined as the ratio of overall effective reflected beam width to the diameter of the receiver:

$$c = \sum_{i=1}^{n} t_i / (2 * r). \tag{4}$$

Thus, by using equations (3) and (4), the optical efficiency and concentration rate of LFRSC can be determined.

Analysis of the optical efficiency and concentration rate of LFRSC. Based on the above presented model, a computer program for the analysis and optimal design of LFRSC is developed. The dependences of optical efficiency and the concentration ratio of the LFRSC on the parameters as the focal distance, the mirror width, the distance between the mirrors and the angle of incident rays are investigated.

In Fig. 5, the dependences of optical efficiency and concentration rate on the focal distance are presented. The parameters used during calculations are: the radius of the tube – 50 *mm*, mirror width – 120 *mm*, distance between the mirrors – 20 *mm*, the total number of mirrors – 10. The dependences are presented for 0^0, 45^0 and 60^0incident angles.

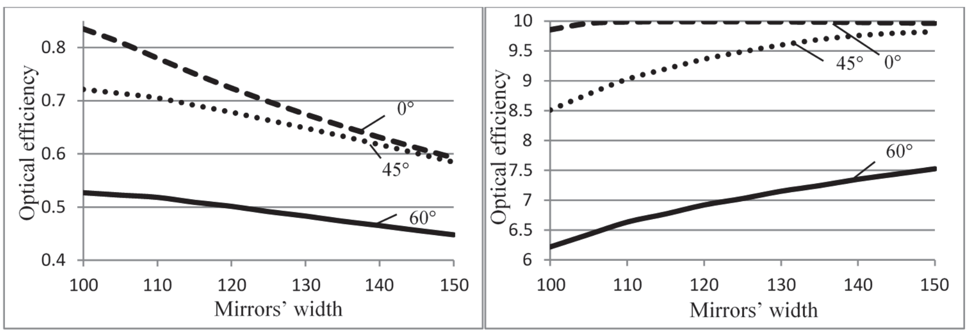


a) b)

Fig. 5. Optical efficiency (a) and concentration ratio (b) versus focal distance

It can be seen from Fig. 6 that both the optical efficiency and concentration rate increase by increasing the focus distance. Starting from some values of the focus distance (700…800 *mm*), the concentration ratio is increasing slowly due to the reduction of shading and blocking effects. As it could be expected, the optical efficiency and concentration rate decrease with the increase of the light incident angle.

In Fig. 6, the dependences of optical efficiency and concentration ratio on the mirror width for different incident angles are presented. The parameters are as in the previous case, and the focal distance is 700 *mm*.

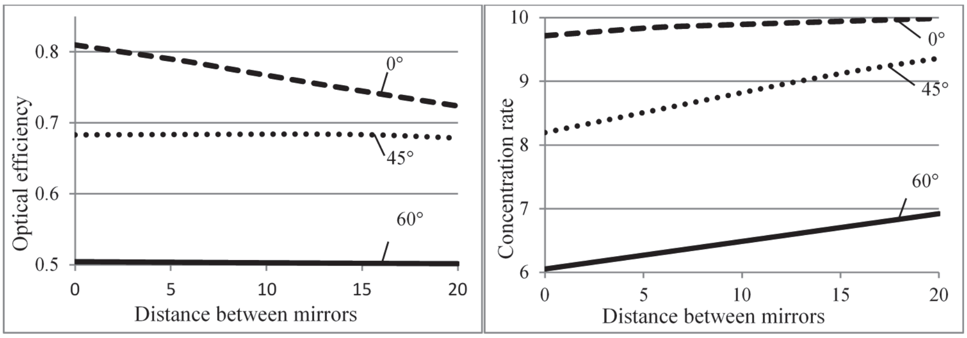


a) b)

Fig. 6. The optical efficiency (a) and concentration rate (b) versus the mirrors' width

As shown in Fig. 6, the optical efficiency decreases with the increase of the mirrors' width. It happens due to the increase in the optical losses due to the shading and blocking effects and the increase in the aperture of the concentrator. The concentration rate increases with the increase in the mirrors' width. With an increase in the incident angle, the optical efficiency and concentration rate decrease due to the increase of the influence of the blocking and shadowing effects. Comparing the dependences of optical efficiency and concentration rate on the mirror width (Fig. 6), it can be concluded that the mirrors' width must be optimized during the design of LRFSC.

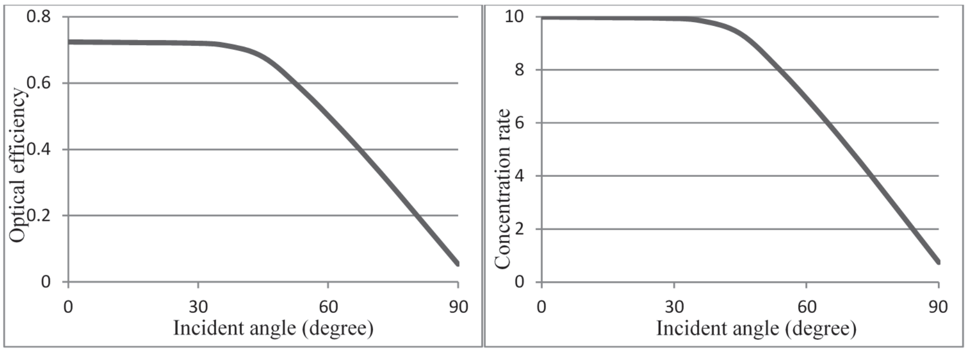
In Fig. 7, the dependences of optical efficiency and concentration rate on the distance between the mirrors are presented. The rest of parameters are the same and the mirror width is 120 *mm*.



a) b)

Fig. 7. The optical efficiency (a) and concentration rate (b) versus distance between the mirrors

As it is expected, the optical efficiency decreases with the increase in the distance between the mirrors. Due to the influence of the shading and blocking effects, the concentration rate increases with the increase of the distance between the mirrors. It follows that the distance between the mirrors also must be optimized during the design to obtain the required optical efficiency and concentration rate. Note that the optical efficiency and concentration ratio are higher when the incident angle is small, as it could be expected.



a) b)

Fig. 8. The optical efficiency (a) and concentration rate (b) versus incident angle versus: a - optical efficiency, b - concentration ratio

It can be seen from Fig. 8 that the optical efficiency and concentration rate are nearly constant when the incident angle is between 0 and 40 degrees, and then after 45 degree, they sharply decrease. Thus, LFRSCs are operating effectively during the daytime, but in the morning and evening, the efficiency reduces significantly due to the shading and blocking effects.

Conclusions

1. The developed mathematical model allows to determine the optical efficiency and concentration ratio of Linear Fresnel Reflector Solar Concentrators (LFRSC), depending on all parameters. The developed computer program allows to analyze the optical efficiency and concentration ratio of LFRSC.
2. The shading and blocking effects are the main optical losses in LFRSC. LFRSC are collecting the solar rays during the daytime more effectively when the incident angle of rays is small (up to about 45 degrees).
3. To increase the optical efficiency and the concentration rate of LFRSC, the focus distance can be as high as possible. But the increase in the rate of the optical efficiency and concentration rate reduces at higher values of the focal distance. Therefore the focal distance must be optimized during the design.
4. The mirror width and the distance between the mirrors must be optimized to get the required optical efficiency and concentration rate.

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ԱՐԵՎԱՅԻՆ ԷՆԵՐԳԻԱՅԻ ՖՐԵՆԵԼԱՅԻՆ ԳԾԱՅԻՆ ԱՆԴՐԱԴԱՁՆՈՂ ԿՈՆՑԵՆՏՐԻՉԻ ՊԱՐԱՄԵՏՐԵՐԻ ՎԵՐԼՈՒԾՈՒԹՅՈՒՆ

Հետազոտվել են արևային էներգիայի ֆրենելային գծային անդրադարձնող կոնցենտրիչի օպտիկական արդյունավետությունը և կոնցենտրացման աստիճանը: Մշակվել են մաթեմաթիկական մոդել և քոմփյութերային ծրագիր: Հետազոտվել են օպտիկական արդյունավետության և կոնցենտրացման աստիճանի կախվածությունները տարբեր պարամետրերից: Ցույց է տրվել, որ արևային էներգիայի ֆրենելային գծային անդրադարձնող կոնցենտրիչների նախագծման ընթացքում ֆոկուսային հեռավորությունը կարող է մեծացվել, և որ պահանջվող օպտիկական արդյունավետությունը և կոնցենտրացման աստիճանը ստանալու նպատակով հայելիների լայնությունը և դրանց միջև հեռավորությունը պետք է օպտիմալացվեն:

Առանցքային բառեր. գծային ֆրենելային կոնցենտրիչ, արևային, հայելի, օպտիկական արդյունավետություն, կոնցենտրացման աստիճան, ֆոկուս, անդրադարձիչ:

Р.Р. ВАРДАНЯН, В.К. ДАЛЛАКЯН

АНАЛИЗ ПАРАМЕТРОВ ФРЕНЕЛЬНОГО ЛИНЕЙНО-ОТРАЖАЮЩЕГО КОНЦЕНТРАТОРА СОЛНЕЧНОЙ ЭНЕРГИИ

Исследованы оптическая эффективность и степень концентрации френельного линейно-отражающего концентратора солнечной энергии. Разработаны математическая модель и программное средство. Исследованы зависимости оптической эффективности и степени концентрации от различных параметров. Показано, что при проектировании френельных линейно-отражающих концентраторов солнечной энергии фокусное расстояние может быть увеличено. Для получения необходимой оптической эффективности и степени концентрации ширина зеркал и расстояние между ними должны быть оптимизированы.

Ключевые слова: френельный линейный концентратор, солнечный, зеркало, оптическая эффективность, степень концентрации, фокус, отражатель.