DIMENSIONING CALCULATIONS FOR A MODULAR FRESNEL MIRROR DESIGNED FOR A 25 KW STIRLING SOLAR ENGINE

Camelia PETRE[1], Stoian PETRESCU[2], Michel FEIDT[3],
Monica COSTEA[2], Octavian MĂLĂNCIOIU[2], Vlad MARIŞ[4]

The paper proposes an original geometrical solution for a polygonal Fresnel mirror designed to drive a solar Stirling engine. The Linear Fresnel designs use lower cost mirrors than troughs, and avoid the need for expensive heliostats in a power tower design. The system uses long flat mirrors at different angles focusing sunlight on concentrated radiation receiver.

Starting from a given power of a solar Stirling engine among the worldwide used ones, by taking into account some geometrical aspects and an original orientation for the polygonal Fresnel mirror modules, the required number of mirrors, the total surface, and volume dimensions were determined.

Keywords: polygonal Fresnel mirror, solar energy, Stirling engine.

1. Introduction

Renewable energy resources – such as wind and solar energies – cannot produce power steadily, since their power production rates change with seasons, months, days, hours etc. The cost issues depend mainly on how research and developments can be successfully carried out in these areas. Extensive public and private researches, and development efforts to achieve technological breakthroughs, are required to bring these technologies to commercial maturity.

Of the developed renewable technologies, Concentrating Solar Power (CSP) is possibly the most adaptable. It can be built in a range of sizes, from few kW up to several hundred MW [1]. It can be configured with varying levels of storage to suit local weather conditions and to meet the requirements of the local grid operator. Different simulation models for solar concentrators for CSP were developed to obtain the irradiance distribution on the absorber [2].

The Linear Fresnel designs use lower cost mirrors than troughs [3], and avoid the need for the expensive heliostats inherent in a power tower design.

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[1] Assoc. Prof., Mechanical Engineering Faculty, University "Politehnica" of Bucharest, Romania
[2] Prof., Mechanical Engineering Faculty, University "Politehnica" of Bucharest, Romania
[3] Prof., Laboratoire d'Energétique et Mécanique Théorique et Appliquée, University "Henri Poincaré" of Nancy, France
[4] PhD student, Mechanical Engineering Faculty, University "Politehnica" of Bucharest, Romania

The ‘Fresnel mirror’ type of CSP system is broadly similar to parabolic trough systems but instead of using trough-shaped mirrors that track the sun, it uses long flat mirrors at different angles that have the effect of focusing sunlight on one or more pipes containing heat-collecting fluid which are mounted above the mirrors [3], or on concentrated radiation receiver [4].

The use of the Fresnel mirrors delivers the traditional benefits of such a system, namely small reflector size, low structural cost, fixed receiver position without moving joints, and non-cylindrical receiver geometry. As for the realization of the modular Fresnel lenses, the technologies used in large flat panel displays are expected to provide the mass production of the concentration optics.

An optimum convex shaped nonimaging Fresnel lens following the edge ray principle is presented in [5]. The lens is evaluated by tracing rays and calculating a projective optical concentration ratio.

Then, the design of a linear Fresnel lens (LFL) according to Fermat's principle is slightly modified with respect to used technology for mass production from glass [6]. Also, a combination of linear Fresnel lenses with PV cells may reduce cost of autonomous solar installations [6].

Relative to the previous work, the paper proposes an original geometrical solution for a polygonal Fresnel mirror designed to drive a solar Stirling engine.

Our geometric design solution leading to a high concentration factor consists of replacing the flat Fresnel mirrors by polygonal modules containing a three side mirror. The vertical array of the polygonal modules is proposed. For each module, the two external side mirrors are inclined compared to the central side mirror so that all the three concentrate the solar radiation in the receiver. It results that each polygonal module will increase three times the concentration factor. On the other hand, the receiver may have a smaller dimensions and a fixed position that represent clear advantages when compared to the dish Stirling systems.

An example of practical use of our approach is given, namely starting from a given power of a solar Stirling engine among the worldwide used ones, by taking into account some geometrical aspects and an original orientation for the Fresnel mirror modules, the required number of mirrors, the total surface, and volume dimensions were determined.

2. Design of the modular Fresnel mirror

Generally, a solar Stirling engine requires a higher temperature at its hot end than a steam generation system. Hence, the concentration factor should have significantly high values that would need large flat Fresnel mirror.

Our geometric design solution leading to a high concentration factor consists of replacing the flat Fresnel mirrors by polygonal modules containing a three side mirror. A solar concentration system using vertical arrays of polygonal modules is illustrated in Figure 1. One can see the two external side mirrors that are inclined compared to the central side mirror so that all the three concentrate the solar radiation in the receiver (see also Figure 2).

It results that each polygonal module will increase three times the concentration factor. On the other hand, the receiver may have a smaller dimensions and a fixed position that represent clear advantages when compared to the dish Stirling systems.

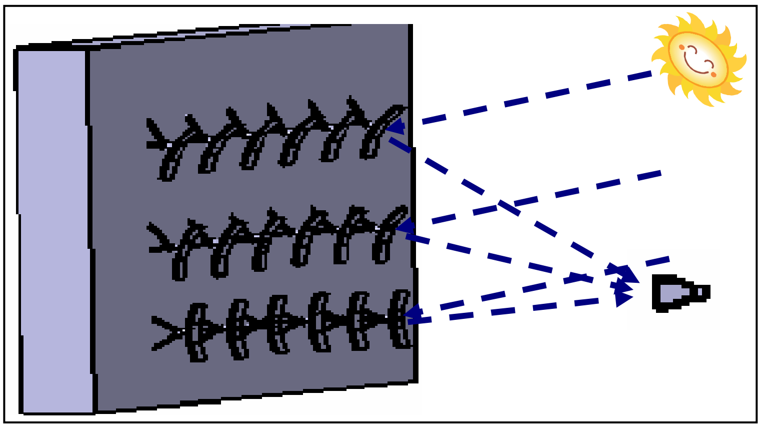

Fig. 1. Vertical positioned Fresnel mirror modules, oriented on an East-West direction (side view) [7]

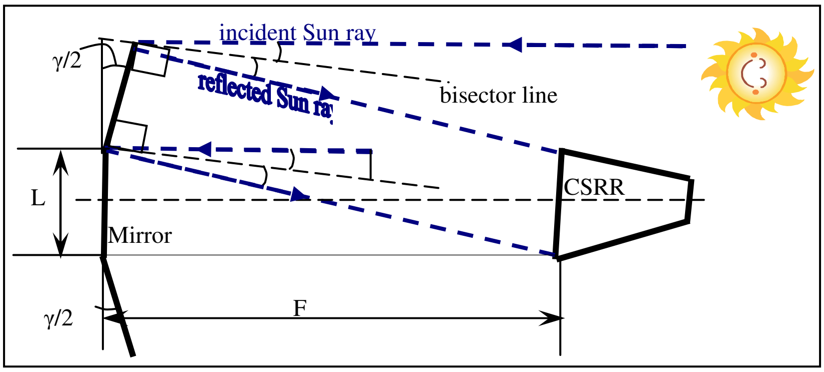

Fig. 2. Three sides Fresnel mirror – optimal rotation angle between sides [7]

This optimal rotation angle between the three sides of the Fresnel module mirror, namely γ/2 angle, was recently determined by the authors in a previous paper [7]. This angle represents the rotation of the upper side mirror with respect to the middle side. By reasons of symmetry, the bottom side mirror is rotated inversely with the same angle $\gamma/2$ that is determined as:

$$\frac{\gamma}{2} = \frac{arctg\left(\frac{L}{F}\right)}{2} \tag{1}$$

where L represents one mirror length; F is the distance from the mirror to the receiver.

Also, the optimal rotation angles in horizontal and vertical planes were derived [7], so that from geometric point of view, the Fresnel mirror modules are optimized (in such a way to reflect maximum in the receiver).

3. Practical situation of use

The aim of this research is to determine the required number of mirrors, the total surface, and volume dimensions of such a solar system suited for a given power solar Stirling engine among the worldwide used ones.

An example of practical use of our approach is given for the NS-03M Solar Stirling engine operating on the Vanguard solar assembly with a parabolic dish mirror of 11 m, producing 25 kW at 32.84 % total efficiency [8].

It is obvious that the surface of the dish mirror is about $S_{DM} = 95\ m^2$.

Specific calculations allowed obtaining the number of required polygonal modules of Fresnel mirrors, oriented on an East-West direction.

For the Fresnel module, we propose the following arrangement: one module is composed by two polygonal Fresnel mirrors, each polygonal Fresnel mirror of dimensions 1mx2m and being composed of three plane mirrors, as represented in Figure 3.

Thus, the surface of one polygonal Fresnel mirror is $S_{FM} = 2m^2$.

It is easy to deduce the number of Fresnel mirrors to insure the same surface caption of the solar rays:

$$N_{FM,S} = \frac{S_{DM}}{S_{FM}} = 47.5 \text{ Fresnel mirrors} \tag{2}$$

But, one should take into account that the aim is to drive the given power engine, so an interception efficiency is to be considered; it takes into account the shadow factor and $\cos\varphi$ factor (the mirror surface is not entirely used, when solar radiation comes on an incident angle φ, different then 90^o) and the fact that not the entire incident radiation on the mirror surface arrives to the receiver. A usual value of this efficiency is about 0.7. Thus, the total required number of Fresnel mirrors is:

$$N_{FM} = \frac{N_{FM,S}}{\eta_{\text{intercep}}} = 67.85 \text{ => 68 Fresnel mirrors} \tag{3}$$

leading to a total caption surface of 136 m^2.

Let us compute now the geometric concentration factor:

$$C_G = N_{FM} \cdot N_{sides} \cdot C_{SR} \tag{4}$$

where N_{sides} represents the number of Fresnel mirror sides, i.e. the number of plane mirrors that form the module; in our case, it is equal to 3;

C_{SR} is the concentration factor of the second receiver, as seen in Figure 3.

The second receiver is designed to have the shape of a cut pyramid having the one base as the same dimensions as a mirror side and the other base having the length of each side three times smaller than the first base one. In this case, $C_{SR} = 3\text{x}3 = 9$.

Coming back to relation (4), the numerical value of the geometric concentration factor is 1836.

This factor is to be compared with the Vanguard geometric concentration factor, which is 2800 [8]. We see that the required concentration factor (2800) is not entirely ensured. This will have an effect on the temperature in the Concentrated Solar Radiation Receiver, which will decrease a little bit. As a consequence also the efficiency of conversion of solar energy into electrical energy will decrease, probably from 32.84 % to something about 27 %. This is still a very good efficiency. In addition to that, because the system now have the Stirling Engine stationary on the earth, or on a platform of several meters high, it could provide very good condition for Cogeneration. This will provide a total efficiency of the system about 80-85 %, which is much higher than 32.2 % the efficiency of the Vanguard System.

4. Overall dimensions

The polygonal Fresnel modules are oriented on an East-West direction, as the Sun tracking system is simpler and more efficient.

We propose an array of three modular stages, as seen in Figure 3.

As the total number of Fresnel mirrors is 68, on three stages it comes up about 24 Fresnel mirrors each stage (by rounding up to the nearest even integer for assembly reasons).

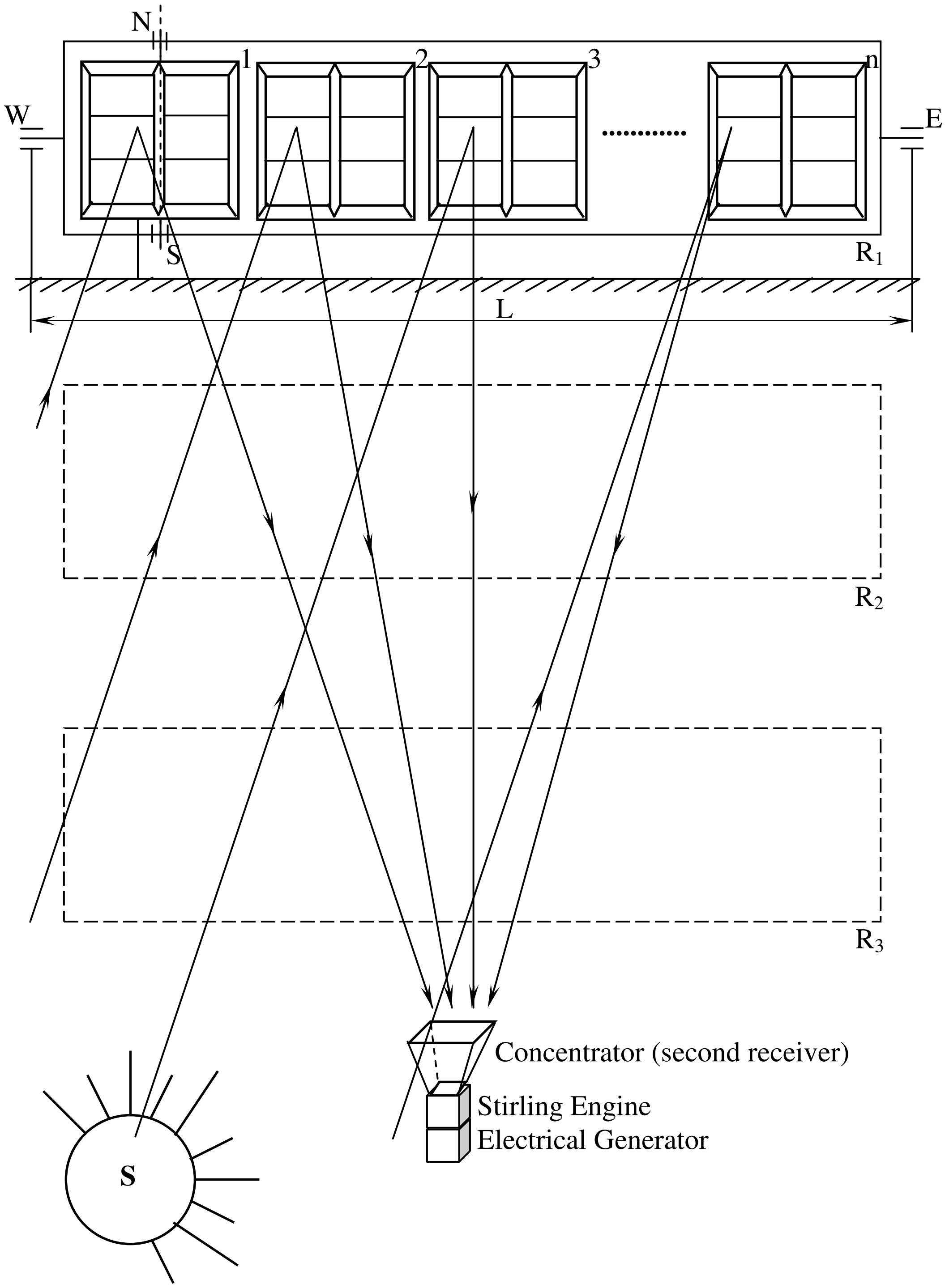

Fig. 3. Assembly of polygonal Fresnel mirror modules

One Fresnel module is composed by two Fresnel mirrors, thus 12 modules each stage are required.

As one module has the dimensions of 2 m x 2 m and we consider 50 cm between two modules, the required length is about 30 m. The height of the three stages is about 8 m considering 2 m the height of one stage, 50 cm between two stages and 1 m from the ground.

5. Conclusions

We developed a new concept of polygonal module of Fresnel mirror providing high concentration factor. The modular array of polygonal Fresnel mirror proposed in this paper is expected to guarantee the heat input in the concentrated solar radiation receiver necessary to drive the NS-03M Solar Stirling engine now operating on the Vanguard solar assembly with parabolic dish mirror. Mathematical treatments for evaluating the image performance and concentration efficiency were presented with illustrations of the new concept.

The proposed vertical arrangement of the Fresnel mirrors has some important advantages, namely the required earth surface is significantly reduced, the system is more suitable for cogeneration applications; the economic aspect is also an advantage as the engine could run on the earth in a fix position, without being necessary to mount it at a high level in the focal point of the dish mirror, and move together with the mirror (as it is done usually in the Stirling Solar/Dish systems).

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