Development of Micro Mirror Solar Concentrator

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Abstract: - The low cost micro facet solar concentrator is proposed. Large number of small flat mirrors is situated at parabolic surface to approximate large parabolic mirror. Low cost commercial flat mirrors can be used for manufacturing of such concentrator. Geometrical analysis show that this concentrator will have concentration rate of some hundreds suns. Rough estimations show that the cost of the concentrator should be approximately $ 55 per square meter of concentrator surface.

Key-Words: - solar concentrator, flat micro mirror, automatic assembly

1 Introduction

At present interest in solar energy is growing [1] - [3]. Two main approaches are used to create solar power plants. One of them is connected with photovoltaic transformers of sunlight to electric current, and the other is connected with the heating of a work liquid or gas and its use in heat engines (turbines or Stirling motors). Both types of solar power plants use solar concentrators to improve efficiency of solar energy transformation. There are three main types of concentrators: parabolic trough concentrators, parabolic dish concentrators, and tower concentrators. Parabolic trough concentrators permit temperatures of 400^oC. Tower concentrators give temperatures of 600^oC, and parabolic dish concentrators give 750 ^oC. The higher temperature allows us to obtain higher efficiency of the solar power plant. In this article we will consider only parabolic dish concentrators. The main problem of the creation of parabolic concentrators is the high cost of their manufacture. There are projects, where the power cell based on a parabolic dish of 87.7 m^2 costs $ 150 000. The authors hope that an industrial version will cost $ 50 000 and will compete with conventional fuel technologies [4]. The cost of $1m^2$ (approximately $500) is still very high. The main reason is that these parabolic reflectors are made from special mirrors. The glass of the mirrors has thickness from 0.7 mm to 1.0 mm [4]. Special technology is needed to make such glass and to obtain the parabolic shape.

In this paper we will show that it is not necessary to make flexible facets. If the size of the facet is sufficiently small, it is possible to make them from conventional flat mirrors. It is possible to use for this purpose low cost commercial mirrors and obtain the concentration rate of some hundreds of suns due to the use of some thousands of flat facets in one concentrator. The cost of such concentrators can be made very low if production of its components and assembly processes is fully automated.

2 Solar concentrator

Let us consider a parabolic dish concentrator (Fig. 1) that contains the receiver placed near the focal point *F*. The design of the parabolic dish concentrator is presented in figure 2. It consists of two layers of triangle cells. Each cell is formed from three bars and three nodes. The cells of the lower layer (Fig. 2) have sizes larger than the cells of the higher layer. Both layers are connected with multiple bars having the same length. Proper selection of the sizes of the upper and lower cells makes it possible to obtain the parabolic shape of the upper layer. Each cell of the upper layer is covered with a flat triangle mirror. In this manner we obtain a dish concentrator with a flat facet approximation of the parabolic shape.

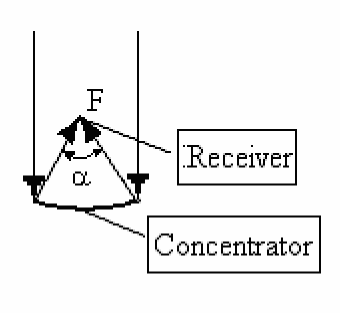

Fig. 1. Parabolic dish concentrator

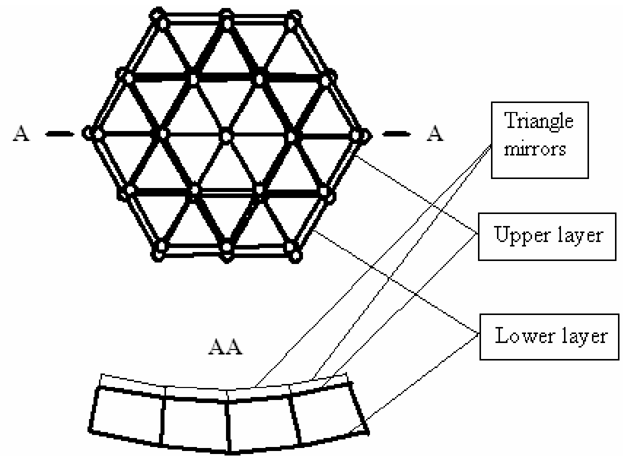

Fig. 2. Design of a flat facet parabolic dish concentrator

3 Concentration ratio of flat facet dish concentrator

Let us consider one triangle mirror of the flat facet dish concentrator (FFDC). We make an assumption concerning the parabolic mirrors: the area of the mirror projection on the horizontal plane has practically the same area as the area of the triangle mirror. If the concentrating angle α (figure 1) is less than 60^o, the error of this assumption is less than 3.5%.

To estimate the concentration ratio let us consider a triangle mirror placed on the perimeter of FFDC. The side of the triangle mirror equals *a*. We will consider the circumscribed circle (Fig. 3) that has the radius *r*.

$$r = \frac{2}{3} \times a \times cos 30° = \frac{1}{\sqrt{3}} \times a \, . \qquad (1)$$

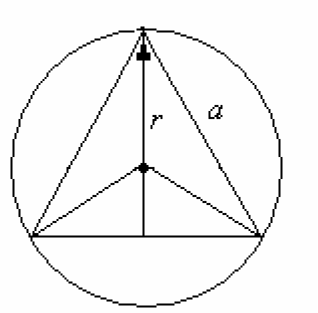

Fig. 3. Triangle mirror circumscribed by a circle

The projection of the circumscribed circle onto the receiver will be an ellipse with small diameter $D''min$ equal to $2 \times r$ and large diameter $D''max$ equal to $\frac{2r}{cos\frac{\alpha}{2}}$ (Fig. 4).

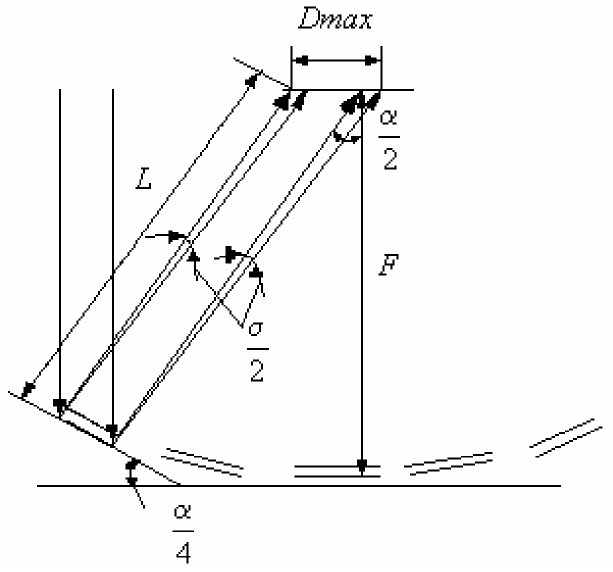

Fig. 4. Projection of outermost triangle mirror onto receiver

To obtain the area that contains all the light rays reflected from the triangle mirror it is necessary to correct the sizes of ellipse taking into account divergence of light rays from the sun. The angle of divergence equals σ. The mean value of σ for the sun is 0.009 radians.

After corrections $D'min$ and $D'max$ will be:

$$D'min = 2 \times r + \sigma \times L\,, \qquad (2)$$

$$D'max = \frac{2 \times r + \sigma \times L}{cos\frac{\alpha}{2}}\,. \qquad (3)$$

From figure 4 we have:

$$L < \frac{F}{cos\frac{\alpha}{2}}\,, \qquad (4)$$

where F is the focal distance of the mirror. Substituting (4) into (2) and (3) we will obtain:

$$D'min < 2 \times r + \sigma \times \frac{F}{cos\frac{\alpha}{2}}\,, \qquad (5)$$

$$D'max < \frac{2 \times r + \sigma \times \frac{F}{cos\frac{\alpha}{2}}}{cos\frac{\alpha}{2}} = \frac{2 \times r \times cos\frac{\alpha}{2} + \sigma \times F}{cos^2\frac{\alpha}{2}} \qquad (6)$$

Without lost of accuracy of our considerations we can slightly increase the sizes of the ellipse and calculate *Dmin* and *Dmax* as follows:

$$D\,min = 2 \times r + \sigma \times \frac{F}{cos\frac{\alpha}{2}}\,, \qquad (7)$$

$$D\,max = \frac{2 \times r + \sigma \times \frac{F}{cos\frac{\alpha}{2}}}{cos\frac{\alpha}{2}} = \frac{2 \times r \times cos\frac{\alpha}{2} + \sigma \times F}{cos^2\frac{\alpha}{2}} \qquad (8)$$

where

$$r = \frac{a \times \sqrt{3}}{3}\,. \qquad (9)$$

Different triangle mirrors have different orientation relative to the receiver. Corresponding ellipses also will have different orientation (Fig. 5).

If we make the receiver a circle with diameter equal to *Dmax*, this receiver will collect all the light rays reflected from the flat triangle mirrors. The area of this receiver is:

$$A_r = \frac{\pi \times D^2\,max}{4}\,. \qquad (10)$$

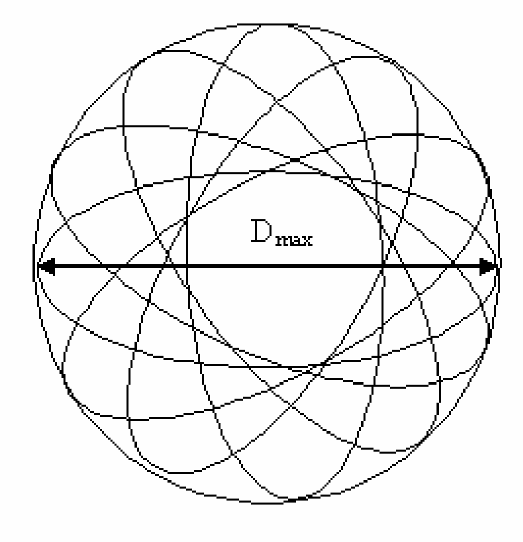

Fig. 5. Ellipse orientation on the receiver

Now we will calculate the total area of all flat triangle mirrors. Let us consider different zones of the solar concentrator (Fig. 6).

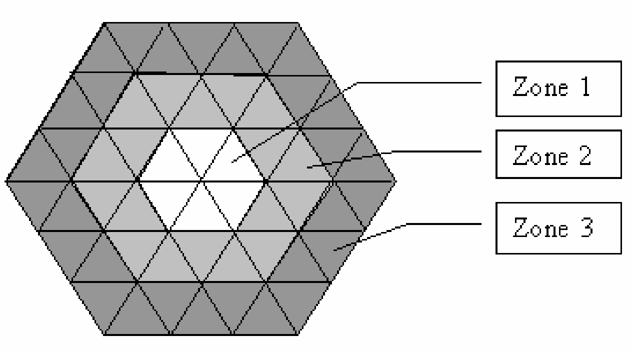

Fig. 6. Zones of triangle mirrors of solar concentrator

It is easy to calculate the number of triangles in each zone. The first zone contains 6 triangles, the second zone contains 18 triangles, and the third zone contains 30 triangles. The general formula of number of triangles in the *i*-th zone is:

$$n_i = 6 + 12 \times (i - 1) \qquad (11)$$

The total number of triangles in the solar concentrator we will calculate as a sum (*N)* of arithmetical progression.

$$N = \frac{2\times 6 + 12\times(n-1)\times n}{2} = 6\times n^2 , \qquad (12)$$

where *n* is the number of zones.

If the triangle side is *a* the total area of the solar concentrator is:

$$A_c = \frac{N\times a^2 \times sin 60°}{2} = \frac{6\times n^2 \times a^2 \times \frac{\sqrt{3}}{2}}{2} = \frac{3\times\sqrt{3}\times n^2 \times a^2}{2} \qquad (13)$$

Concentration ratio η can be obtained from the equation

$$\eta = \frac{A_c \times \eta_m}{A_r} \qquad (14)$$

where η_m is the reflection coefficient of the mirrors.

To choose the focal distance *F* let us consider the parabola which corresponds to equation:

$$y = \frac{x^2}{4F} . \qquad (15)$$

The solar concentrator uses $2\times\Delta x$ (Fig. 7) at the bottom of the parabola.

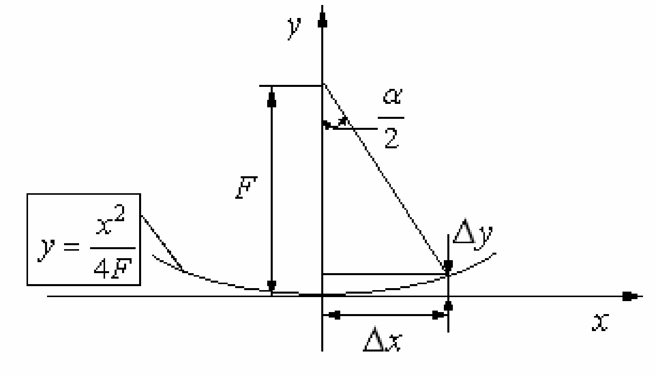

Fig. 7. Parameters of parabolic solar concentrator

The maximal angle $\frac{\alpha}{2}$ of the solar concentrator can be calculated using the equation:

$$\frac{\alpha}{2} = arctg\left(\frac{\Delta x}{F - \Delta y}\right). \qquad (16)$$

From equation (15) we have:

$$\Delta y = \frac{\Delta x^2}{4F} \qquad (17)$$

Substituting (17) into (16), we obtain:

$$\frac{\alpha}{2} = arctg\left(\frac{4F * \Delta x}{4F^2 - \Delta x^2}\right). \qquad (18)$$

It is easy to see that

$$\Delta x = a \times n \qquad (19)$$

From (18) and (19) we have:

$$\frac{\alpha}{2} = arctg\left(\frac{4F\times a\times n}{4F^2 - a^2\times n^2}\right) \qquad (20)$$

Using equation (20) we will select the value *F* in such a manner that angle α will be equal to the maximal angle α^* permitted for this type of concentrator. In this article we choose $\alpha^* = 60°$. From (20) we can obtain the expression for focal distance *F*:

$$F = \frac{a\times n\times\left(1 + \sqrt{1 + tg^2\frac{\alpha}{2}}\right)}{2\times tg\frac{\alpha}{2}} \qquad (21)$$

In Table 1 we present some examples of flat mirror solar concentrator parameters.

For these examples we define the number of zones (*n*), triangle side (*a*) in meters, reflection coefficient of mirrors(η_m=0.9) and calculate the number of mirrors (*N*), focal distance (*F*) in meters, total area of concentrator (A_c) in square meters, area of receiver (A_r) in square meters, and concentration ratio η.

The examples presented in Table 1 show us that flat mirror solar concentrator can give concentration ratios of more than 1 000 suns. This concentration ration is sufficient for the most practical application.

Table 1
Some examples of flat mirror solar concentrator parameters

Number of zones (n)	Number of mirrors (N)	Triangle side (a) (meters)	Focal distance (F) (meters)	Concentration ratio η (suns)
3	54	0.05	0.28	11.5
10	600	0.05	0.933	122
20	2400	0.05	1.866	377
25	3750	0.05	2.332	522
30	5400	0.05	2.8	666.5
40	9600	0.05	3.732	954.2
50	15000	0.05	4.665	1238.6

4 Manufacturing and assembly of flat mirror solar concentrator

Commercial flat mirrors are very cheap. It is relatively easy to cut them for small triangles.

To manufacture and assembly the support frame we propose to use the methods of microequipment technology, described in [5], [6].

We have developed such a type of technology during the last decade. This technology is based on sequential generations of micromechanical equipment [5], [6]. The idea is to obtain micromachine tools and assembly devices comparable with the sizes of components to be produced. In our case the sizes of the bars have an order of 50-70 millimeters. These bars could be produced, for example, from steel tubes having length 50-70 mm, diameter 3-4 mm, and wall thickness near to 0.2 mm. To make these tubes from steel foil it is possible to use machine tools having overall sizes 100-200 mm. The connecting nodes of these parts will have the sizes of 3-5 mm. To produce such nodes it is possible to use micromachine tools with overall sizes of 10-20 mm. It was shown that such machine tools can give good tolerances without the use of super precise technology [7]. Such micromachine tools demand small space, have low energy consumption, and can be organized in desk top factories that realize mass parallel manufacturing process [5]. This process permits production which has costs comparable to the cost of the materials [6].

The assembly of the support frame will be made using micromanipulators with computer vision control [8] - [11]. At present we are developing microassembly devices with computer vision systems. For this purpose we have developed various algorithms for image recognition based on neural networks. The simplest algorithm LIRA was proved in a microassembly task [8], for shape recognition of micro screws [9], and for different tests, for example, texture recognition [10], handwritten digit recognition [11], etc. Another image recognition system PCNC [12] was proved in screw shape recognition, in texture recognition, face recognition, and handwritten digit recognition. All tests demonstrated good results. We intend to apply this adaptive control based on recognition systems for micro assembly devices including an assembly device for the support frame for solar concentrators.

5 Approximate cost estimation for solar concentrator

First let us estimate the cost of materials for manufacturing a solar concentrator with 50 zones (Table 1). The cost of commercial mirrors is less than $ 20 for 1 square meter. The concentrator has an area A_c = 16.24 square meters. So the cost of the mirrors will be $ 324.8.

To estimate the cost of material for one bar we will calculate the weight of this bar. The weight of one bar is:

$$W_b = \pi \times d_b \times l_b \times t_b \times \rho_{st}, \tag{22}$$

where d_b is the diameter of the bar, l_b is the length of the bar, t_b is the thickness of the bar walls, and ρ_{st} is a density of steel. In this article we take $d_b = 4\times10^{-3}$ m, $l_b = 7\times10^{-2}$ m, $t_b = 2\times10^{-4}$ m, $\rho_{st} = 7\ 800$ kg/m^3. With these values we will have the weight of one bar 1.372×10^{-3} kg. This solar concentrator contains 93 786 bars. The weight of all the bars will be 128.7 kg. To estimate the weight of connecting nodes it is necessary to know their design. In this paper we will roughly estimate the weight of connecting nodes as 0.3 of the weight of the bars. So the weight of the connecting nodes will be 42.9 kg and the total weight of the support frame will be 171.6 kg. The cost of 0.2 mm steel foil at present is approximately $ 0.7 for 1 kg. The cost of materials for the support frame will be $ 120. The total cost of all materials is $ 444.8.

Here we will estimate the cost of micro manufacturing and micro assembly approximately equal to the cost of materials. In this case the cost of the solar concentrator can be estimated as $ 889.6. The cost of each square meter of solar concentrator surface will be about $ 55. To our knowledge this is much cheaper than the cost of existing parabolic solar concentrators.

6 Conclusion

A solar concentrator composed from a large number of small flat mirrors attached to a parabolic dish is proposed. The calculated concentration rate can be more than 1000 suns. A rough estimation of the solar concentrator cost is $ 55 per square meter. This solar concentrator can substantially reduce the cost of solar power plants and will permit application of these concentrators in solar systems for individual home energy service, breaks firing, etc. The support frame can be made using micro mechanical technology based on computer vision systems which is being developed by the authors.

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