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Design and Evaluation of Flat Solar Concentrator

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Abstract- Flat solar concentrators are designed to focus solar radiation in a linear shape. The concentrator is designed to be the primary step in a sequence of steps that eventually generate solar laser. The focused beam from the concentrator output is used to optically pump a lasing medium (iodine medium) which is compressed in a one meter long and 8 mm diameter quartz tube. The design used here is formed of two flat mirrors with the availability of changing the angel between them. The two mirrors are displaced to create a gap between the two mirrors at the line of their intersection. This research was dedicated to focus down the highest intensity of solar radiation so that the optimal operating conditions of the concentrator are achieved. Multiple parameters were changed, and their effects were simulated theoretically. The highest solar photon concentration was established at the bottom line connecting the two mirrors. In this respect, a movable semiconductor spectrometer was applied to study both the focused radiation spectrum and intensity.

Keywords- Solar Laser; Flat Concentrator; Solar Radiation collection.

1. LITERATURE SURVEY

Solar energy plays an important role as a reliable source of renewable energy. The abundance of such source makes it a very convenient source of energy to solve the energy crisis around the world. Egypt is advantageous with high solar energy flux throughout the calendar year. As a result of its location in the ”sun belt” region, the sun shines 9-11 hours a day with 2000 to 3000 $KWh/m^2/year$ of direct solar radiation [1].The main question so far has been ”how to efficiently convert solar energy into other types of conveniently transferable models of energy?”. The challenge here can be divided into two main parts. Part (I) is the fact that solar energy covers a vast range of the electromagnetic spectrum. As an approximation, solar energy spectrum’s peak is in the visible light with a little extinction in the ultraviolet and infrared ranges. Figure 1 shows a typical solar spectrum obtained outside of the lab. Part (II) is to transfer this type of energy over wide distances with minimal degradation. By efficiently collecting solar energy. It can be used as a daily alternative to energy sources currently in use. Most of the techniques studied so far has focused on transferring the solar energy into electricity by creating electron- hole pairs in a photovolatic cell. Though this technique proved efficient in producing electricity, the waste of solar spectrum is relatively large. Also, thermal effects create complications to the system. Transferring the solar energy using photons rather than charge carriers seems as a wise alternative. Photon energy transfer especially if they are in the form of laser beam is believed to dramatically improve the system efficiency.

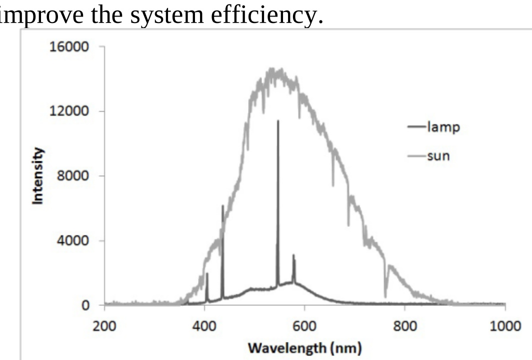

Fig. 1. The graph shows the spectrum for the lamp used in evaluating the design (solar simulator) against the solar spectrum (obtained outside of the lab). There are couple spectrum lines in the source spectrum. The data from those lines was compared to eliminate any cavity (resonance) effects.

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Solar concentrators have been studied along the history. It was considered an efficient method for collecting both sun thermal and optical energy. Many groups have worked on applying solar energy in the daily life [2]. Their design, however, was using curved mirror to collect solar energy. The collected beams were then focused onto Nd:YAG rod which acts as a lasing medium. The laser generated from the solar spectrum was used to fuel electrical Vehicles. Other applications include free space communication [3] and alternative energy source supply [4].

Different collection techniques were applied. Using parabolic trough [5], ring array concentrator [6] and Fresnel lenses in different geometries [5,7–10] are examples of the techniques used. The solar concentration in Ref [9] was performed using a parabolic off-axis mirror to focus the solar radiation onto one of the faces of the fiber optic where the lasing medium is located. Optical losses were found in Ref [8] design arising from cosine, blocking and shadowing losses. The theoretical bases for directly coupling optical broadband solar energy into high narrow spectral range laser beam was discussed in Ref. [11]. This is achieved by pumping molecular ground state Oxygen. Meanwhile, most of the lasing media used in literature were Nd:YAG in different geometries [2,7,10]. Ref. [7] design, for example, utilizes grooved Nd:YAG rods as a lasing medium. The collection was performed using Fresnel lenses in addition to the collection action of the grooves as a light focusing cavity.

Fig. 2. A real live image of the system used. The two mirrors with the availability of changing the angle between them is shown.

2. Experimental Technique & Design parameters

Flat concentrator is simpler to manufacture which guarantees lower cost. This economic factor can result in vast applications. Flat concentrator focuses down the solar radiation in a linear spatial mode. The lasing medium is set up in a linear form. This is achieved using a cylinder quartz tube filled with iodine gas. The cylinder dimensions are 1m long and 8mm diameter.

The concentrator design is a simple two flat mirrors design with a gap in between 1:1.5 cm. The system is shown in figure 2. A schematic of the system with a ray trace shown in figure 3. The light rays would keep bouncing between the two mirrors until eventually collected at the bottom gap between the two mirrors. While testing the concentrator

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performance, the light was collected using a fiber connected to a fiber coupled spectrometer StellarNet (HR4D5161). Many parameters were varied. The angle between the two mirrors was varied while keeping one of them in a completely vertical plane orientation. The dimension of the two mirrors was changed to increase the path along which the light beams are collected. Finally, the effect of the edge collection and the spatial distribution of light were studied to ensure the beam collection quality of the concentrator. The concentrator is designed to be used eventually with the broad band solar radiation. To simulate the sun effect, a light source with multiple wavelengths was used. The spectrum of the light source used against the solar spectrum outside the lab is shown in figure 1. The light source enabled a constant output for accurate comparison purposes. The multiple wavelengths feature ensured the elimination of any resonance effects.

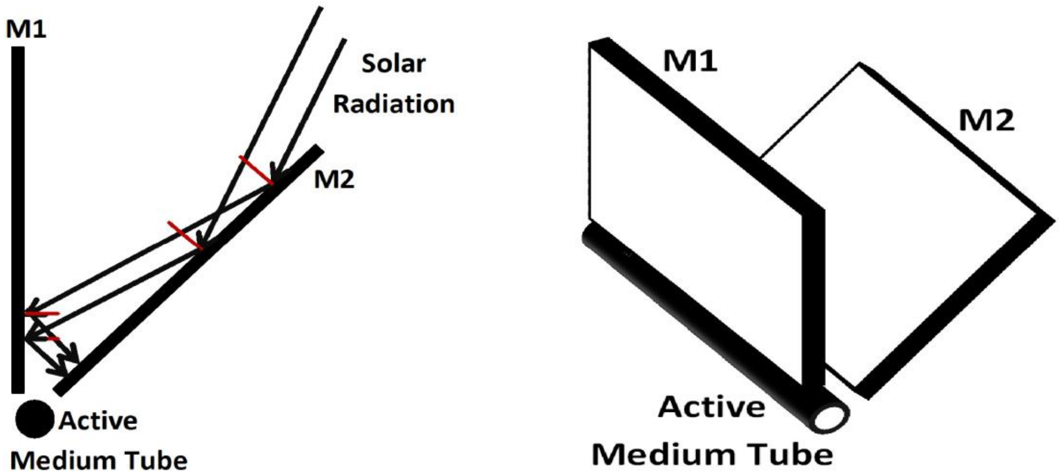

Fig. 3. The figure on the left shows a solar rays traces inside the concentrator. The figure on the right shows a schematic of the system used.

While designing the concentrator, the main target was to contain as many re- flections inside the mirrors' gap as possible. Changing the angle between the mirrors enables collecting higher number of incident beams. The relation between the angle and the intensity of the collected beam is shown in the figure 4. The figure shows saturation effect for decreasing the angle beyond 20 degrees. At each angle, the spectrum was collected for the solar lamp used. At each angle, the spectrum was performed twice, and the average was calculated for the two trails. The shown graph is only for the 545.808 nm spectral line. The calculations were repeated for different wavelengths to eliminate the saturation effect. The immediate conclusion established is that decreasing the angel between the two mirrors is essential for an efficient collection. Unfortunately, this is limited by the dimensions of the measuring optical fiber on one hand i.e. the insertion of the measuring fiber tip between the two mirrors base implies larger angles. On the other hand, the dimensions of the quartz tube limit the smallest angle limit that can be achieved.

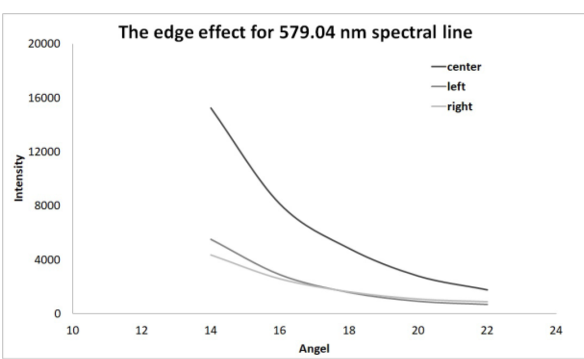

Fig. 4. The effect of changing the angel between the two mirrors. It appears that as the angel increases the intensity of the collected beams decreases. Increasing the angel beyond 28 degrees affects the signal drastically.

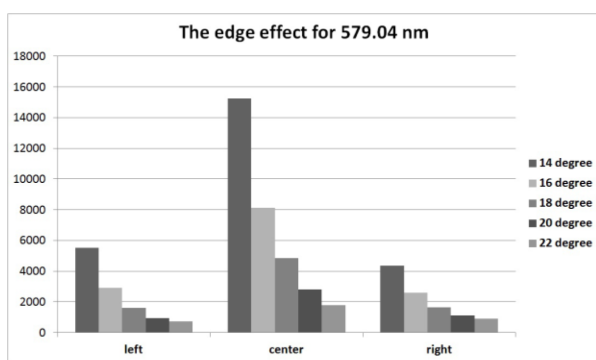

Fig. 5. The edge effect for different concentrator angels. It appears that the signal degradation decreases while increasing the angel between the mirrors.

The second parameter studied was the edge effect in figures 4, 5. The further are the beams from the center of the concentrator, the more scattered rays drift away from the concentrator. Away from the center the signal decays. The decay factor decreases while increasing the concentrator angel. The decay factor is inversely proportional to the signal to input ratio. This ratio changes from 32 - 43 % range for 14-degree concentrator angel to 45 - 49 % range for 22-degree angle. This is shown in figure 5 for two spectral lines.

Another parameter studied was the effect of the concentration path. The mirror designs used were 1m ∗ 1m and 1m ∗ 0.5m rectangular flat mirrors. The horizontal dimension was kept 1m in both cases while the vertical dimension changed between 1m and 0.5m. The vertical dimension is the direction along which the solar beams are incident that is why the vertical dimension is called the concentration path. In fact, increasing the collection path causes shadowing effects at smaller angels.

This means that the spectrum collected from the large concentrator has higher intensity than the spectrum collected from the small mirror's concentrator. This is shown in figure 6. The deviation from this behavior is attributed the beams' blocking "shadowing effects". The intensity was measured at the different sites of the inclined mirror. The vertical mirror is placed in the same plane as the light source. The horizontal direction is always 1 meter divided into 5, 25, 50, 75 and 95 cm intervals. However, the vertical dimension is different in the two concentrators.

It is divided into 12, 30, 45 in the small concentrator and 70 intervals is added in case of the large concentrator. An intensity map was performed for the two cases. Again, for most of the points, the large concentrator shows higher intensity than the small one.

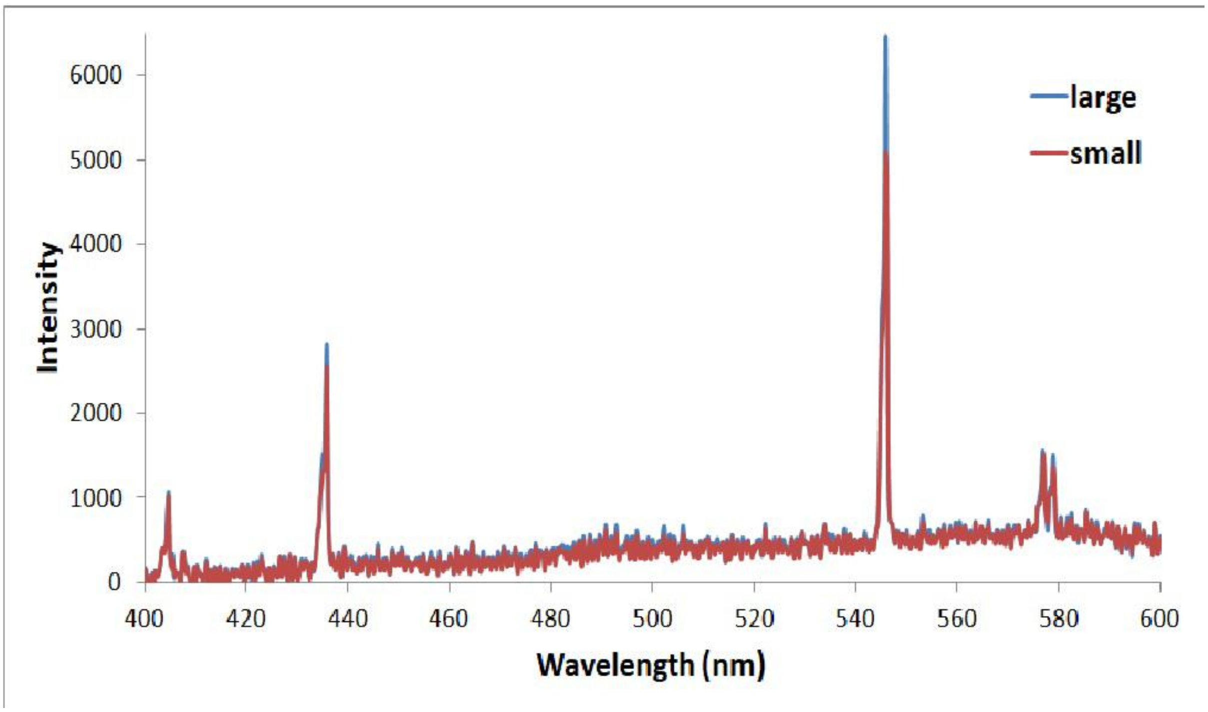

Fig. 6. The figure shows the spectrum collected between the two mirrors. The larger mirror shows larger spectrum peaks.

3. Theoretical Data Simulation

The theoretical calculation was performed under the criteria that the reflected beam from the two mirrors with an angle between them θ is deflected from it is original direction by 2θ. The beam would continuously reflect between the mirrors until the total angle made with the inclined mirror $\alpha+(n-1)\theta \leq 90$, where n is the number of reflections and α is the angle between the original beam and the inclined mirror. This condition implies a normal incidence and hence a retro reflected beam on its original path. The number of reflections is taken as an indicator for the beam intensity since higher number of reflections indicates higher number of beams collected. Figure 7 shows the summation of the calculated number of reflections for all possible incidence angle and then the beam waist part for the most possible

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incidence angles where α = 10 : 40. Both of the two curves show a similar behavior to the one shown in the experimental results figure 4. The two curves were calculated for different angles of incidence and the angle between the mirrors was varied between 4 to 28 with a 2-step size.

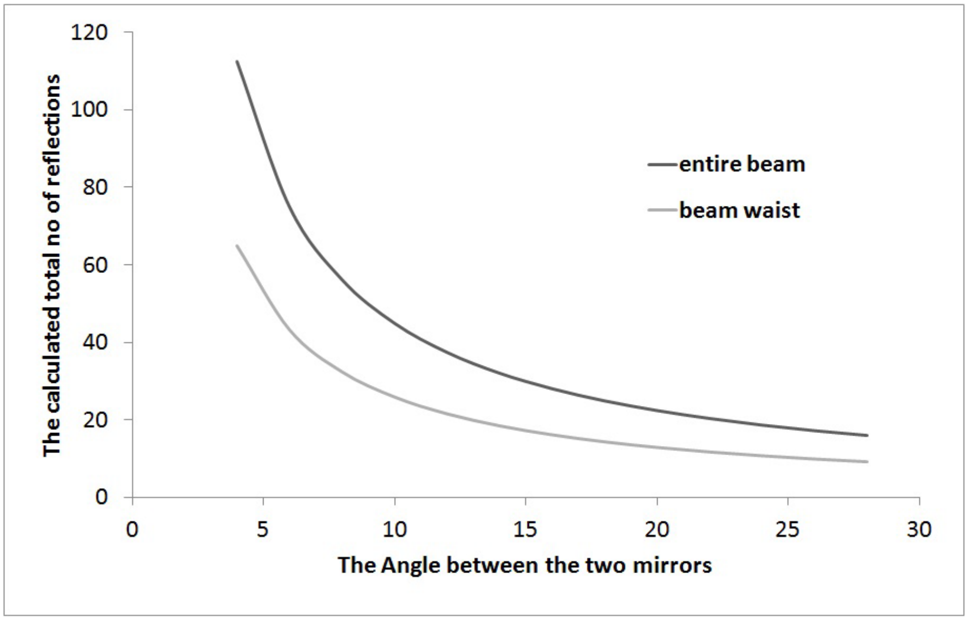

Fig. 7. The angle between the mirrors and the number of reflections (as an intensity indication). The entire beam curve takes in consideration all possible incidence angles. The beam waist curve considers the concentrated part of the beam that propagates about the perpendicular direction from the lamp. This curve also stimulated the behavior at the noon time where the solar radiation intensity is maximum.

It is important to mention that the main difference between this set up {using solar simulator} and the actual solar spectrum is in the directional distribution of the beams. While the solar spectrum is maintained collimated throughout the day, it changes its inclination angel. Between the morning and the afternoon, the solar beams scan through different values of α. At the noon duration, the solar spectrum has higher intensity and as a result the angel dependence would follow the beam waist trend.

The second step was to calculate the penetration depth i.e. how far along the concentrator do the beams propagate before they are retro reflected on the original path. These calculations were performed for both the two concentrator models. Table 1 shows the position of the normal incidence for each angle of incidence and concentrator angle. The zero values mean beams parallel to the inclined mirror and as a result they fully penetrate the concentrator to the lasing medium. On the other hand, the 100 cm values mean beams reflected away from the concentrator after a single reflection. In other words, the smaller the distance of the normal incidence, the higher the intensity of the collected beam. These calculations were performed to ensure that the beams collected are concentrated at the spot of the lasing medium tube. The table 1 shows that the smaller angle between the mirrors, the higher the intensity of the collected beam since all the angles of incidence are collected. It also shows that the strong effect takes place because of the beam waist (angle of incidence between 10 and 40). Finally, it shows that for a concentrator of the dimension 1m * 0.5m the intensity of the collected beams is smaller since the cut-off height will be 50 cm instead of 100 cm in this case.

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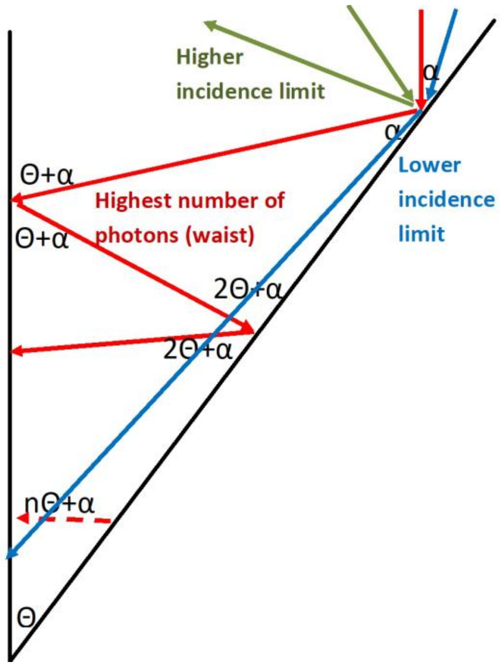

Fig. 8. The beam direction shown. The graph shows the parameters used in the theoretical calculations and the criteria for the beam waist calculation. The solar spectrum is considered collimated. The scanning of it throughout the day changes the direction of the beam. Although the peak exposure (the noon time) takes place at the direction indicated as the beam waist part.

Table 1. The height of normal incidence as a function in the mirrors' angles and the incidence angle.

Angle of incidence	The angle between the mirrors												
	4	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**
0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	17	18	18	17	18	17	18	18	17	18	20	20	19
20	34	34	34	35	34	35	34	34	35	38	37	36	35
30	50	50	50	50	51	50	50	55	53	52	51	50	50
40	64	64	64	65	64	65	68	66	65	65	64	64	65
50	77	77	77	77	80	78	77	77	77	77	77	78	100
60	87	87	87	88	87	87	87	87	88	100	100	100	100
70	94	94	95	94	94	94	100	100	100	100	100	100	100
80	99	99	100	100	100	100	100	100	100	100	100	100	100
90	100	100	100	100	100	100	100	100	100	100	100	100	100

4. CONCLUSION

The collected data implies that as the angel between the two mirrors increase, the intensity of the collected beams decreases. According to the theoretical calculations, this is mainly due to the increased number of the retro or back reflected beams despite the larger number of collected beams i.e. the beams are reflected back outside of the concentrator.

As the collection path increases, the intensity of the collected beam increases. This is shown in the data collected in the 1m*0.5m and 1m*1m concentrators figure 6. This is in accordance with our theoretical calculations in table 1. Any deviation from this behavior is mainly due to shadowing effects. The larger mirror size obscures the beam path from making it to the inside of the concentrator.

The spatial distribution of intensity shows slight decrease towards the edges. This can be attributed to the scattered beams that are reflected at an angle away from the mirrors to the sides. The distribution also shows also a slight increase in intensity towards the bottom figure 5 where the lasing medium tube is located.

The optimal conditions for operation imply using the larger size concentrator to guarantee higher concentration path. The second condition is to minimize the angle between the mirrors. The angle best used is about 15 degrees to leave a room for the lasing medium tube. The lasing medium is an iodine gas in a quartz tube with dimensions 1m long and 8mm diameter. The original design was assumed to concentrate the beams down with a collection efficiency of 40%. The actual collected data from the spatial light intensity distribution at the center of the concentrator shows a concentration in the range 61% to 75%.

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