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Energy Yield Analysis for Fixed Linear Fresnel Reflectors Type Concentrated Solar Power System in the UAE

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Abstract: Concentrated Solar Power (CSP) is a commonly researched branch of renewable energy technologies. Linear Fresnel Reflector (LFR) systems are also not a very niche topic in CSP. This study aims to approach the LFR systems in a quite different concept, by considering a new way of solar tracking. In this study, the Fresnel mirrors are fixed on a rotating platform which can track the sun's azimuth angle by rotation. An analytical model to populate the mirrors on a defined area is developed and using the model a mirror setup is generated. Moreover, the effects of the structural parameters on the solar yield are analyzed by using a ray tracing software. When analyzing the solar yield the study keeps focus on the optical parts of LFR systems.

Key words: CSP, LFR, rotation, optical, tracing, yield

INTRODUCTION

Global rising temperature as a result of huge carbon emissions, volatile oil prices and concerns of governments about security of energy supply caused rapid growth in the renewable energy market, especially in solar Thermal-Concentrated Solar Power (CSP) technologies (Crabtree and Lewis, 2007; Mills, 2004). In this study, the Fresnel mirrors are fixed on a rotating platform which can track the sun's azimuth angle by rotation. An analytical model to populate the mirrors on a defined area is developed and using the model a mirror setup is generated. Moreover, the effects of the structural parameters on the solar yield are analyzed by using a ray tracing software. When analyzing the solar yield the study keeps focus on the optical parts of LFR systems.

Motivation: Growth in the economy and increasing living standards are welfare indicators that every country is proud of. These developments are closely bound to their energy consumption. With the world having a population and economic growth trend as of now, we may assume that the energy consumption will increase even quicker. Increasing oil prices and global climate changes are closely affecting the supply of energy required by this inevitable growth. After the global oil crises in 1973 and 1979, the world focused on developing renewable energies. New technologies were experimented and implemented in large scales which were researched in the past, some having a history of more than two centuries. The first big scale parabolic trough, dish, solar tower and solar chimney plants were installed as a consequence of theses crises. Until that time due to market resistances and insufficient financial and political supports of governments, the developments in this field were delayed. Due to global rising temperature as a result of huge carbon emissions, volatile oil prices and concerns of governments about security of energy supply caused rapid growth in the renewable energy market, especially in solar thermal-concentrated solar power-technologies (Crabtree and Lewis, 2007; Mills, 2004) .

The most common solar thermal power concept-parabolic trough- is more costly in comparison to linear Fresnel due to the curved mirrors and tracking mechanism. Using Fresnel reflectors seems as an attractive option to solve the cost problem Larbi *et al.* (2000). The classical Linear Fresnel Reflector (LFR) concept is cheaper in comparison to other solar thermal power technologies. But still in LFR technology every mirror is tracking the sun autonomously to reflect the incident sunrays to the receiver which also adds to the total cost of the systems. The particular specialty of this project is to contribute in developing a low cost CSP system which will generate electricity with lower cost per kWh of electricity. Omitting the tracking system for each mirror and populating extra flat mirrors on a platform can achieve this. The platform as a whole is capable of

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rotating and tracking the suns motion in azimuth angle. As a result to develop a robust, efficient, scalable and modular mirror design is aimed.

Objective: The study focuses on developing a mirror setup as Linear Fresnel Reflector (LFR) for concentrated solar power utilization purpose. Analyzing the effect of structural errors on the solar yield (sensitivity analysis) of the LFR module is also an important target of this study. The existing module is also based on the principle fixed mirrors on a rotating platform. Therefore, this study will show how to calculate a mirror setup for LFR. Then the calculated mirror setup will be compared with the existing mirror setup using ray tracing software. For the sensitivity analysis, the existing mirror setup will be used, so that, the results can be applied and experimented without waste of time and resource. The concept will be based on extra flat plate mirrors which will be fixed on a rotating platform to track the sun's motion in azimuth direction throughout the day. When positioning the mirror strips in the mirror setup, they should be positioned in a formation that blocking and shading of mirror strips will be minimally.

The RAK research and innovation center in Ras al Khaimah, United Arab Emirates can use the study as a base for further experiments on an existing LFR module available. Therefore, the solar data of this region will be used in the calculations and simulations. The existing module is also based on the principle fixed mirrors on a rotating platform, yet, the positioning methodology of the mirror setup and efficiency factors are unknown. Therefore, this study will show how to calculate a mirror setup for LFR. Then, the calculated mirror setup will be compared with the existing mirror setup using ray tracing software. For the sensitivity analysis the existing mirror setup will be used, so that, the results can be applied and experimented without waste of time and resource.

Literature review

Solar radiation: The solar radiation reaches outside of the atmosphere through vacuum of space. During its journey through the atmosphere to the earth surface solar radiation gets weakened because of scattering, reflection and absorption.

The incoming solar radiation is reduced approx. to half of its initial value when reflected and absorbed by environmental factors such as clouds, atmospheric gases and aerosols. Beside that the, earth radiates some amount of the energy from its surface to the sky. Again a significant amount of this radiation is returned to the earth by the greenhouse gases. From the extraterrestrial solar radiation the remaining solar rays reaching the surface are called direct radiation or beam radiation. Some portion of the absorbed, reflected or scattered solar radiation in the atmosphere returns to earth surface in form of short wavelength radiation. Photovoltaic panels can utilize global solar radiation where for solar thermal systems direct beam radiation is useful (Garg, 2009).

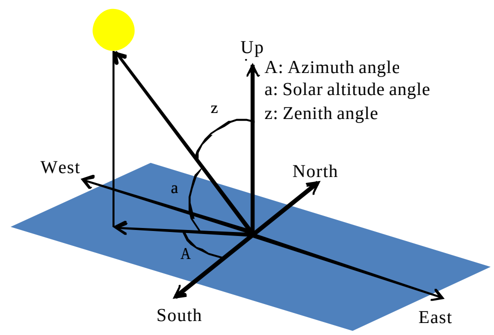

Fig. 1: Sun path and it's correspoding angles

Sun's path: While sun and earth are moving in their determined orbits in the space, solar systems require tracking the sun where their efficiency is directly related with incidence angle of the sun rays. For tracking the sun its position in the sky with respect to a reference point on the earth should be determined accurately. The sun's position can be defined by the following angles as also shown in Fig. 1.

A is the Azimuth angle and defines the angle between the projected position of the sun on the horizontal plane and the south direction. z is the zenith angle and is the deviation of solar position from the normal vector (up direction). α is the solar altitude angle or elevation angle. Zenith angle and solar altitude angle can be substituted for each other (α = 90-z) (Mertins, 2009).

The sun angles are not only depending on the time of the day but also on the declination at the respective day of the year. To put in other words the pattern of sun's path in the sky changes throughout the year (Walter and George, 2005).

The sun's height (solar altitude angle) is ranging from 0-90° where the azimuth is ranging from -180° to 180°. The East is defyned per definition with A = -90° (Gharbi *et al*., 2011).

Concentrated solar power: Solar power has relative low density which must be collected and concentrated for efficiently utilization. Solar power can be concentrated using refracting or reflecting optical surface. Reflecting optical surfaces are most commonly used method for commercial purposes so the study will focus on this side of CSP.

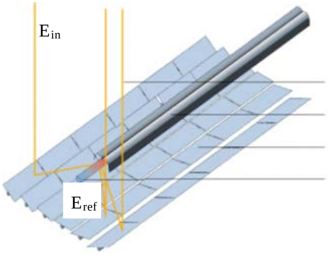

Fig. 2: Basic components of a linear Fresnel reflector module (Haberle *et al.*, 2002)

By line focusing plants, the receiver and the reflector mirrors are positioned parallel to each other. Parabolic trough and linear Fresnel systems count in this category of CSP.

Figure 2 presents a closer look to LFR. Primary Fresnel reflector mirrors reflecting (E_{ref}): the incident solar rays (E_{in}) to the receiver tube. In some designs, also, a second stage reflector above the receiver can be included to collect the escaping rays and redirect them back to the receiver.

In a classical linear Fresnel reflector design several mirror strips are populated in parallel along a receiver, which are also called primary mirrors. The primary mirrors are responsible to reflect the incident solar rays to the receiver which is placed at a determined height. The mirrors are populated having a certain distance between each other to reduce shadowing and blocking effects. The receiver consists of an absorber tube and optionally a secondary reflector and insulation. Secondary reflector facing with its reflective surface downwards to the primary mirrors assures to concentrate the escaping rays back on the absorber tube. Closing the secondary reflector with a glass plate from its downside prevents negative effects of dust and convection losses (Mertins, 2009). To achieve reasonable solar efficiency solar tracking is a must for this system. Most common way of tracking is installation of a separate one axis tracking mechanism for every single mirror strip. Another option is moving the receiver and keeping the mirrors fixed. Although, there is theoretical research done on fixed mirrors-moving receiver, commercially it is not applied (Pujol *et al.*, 2006). This study considers extra flat fixed mirrors populated on a rotating platform which is tracking the sun in one axis in other words tracking the azimuth angle of the sun.

MATERIALS AND METHODS

Mathematical modeling of the linear Fresnel reflector

Parameters of mirror design to be used in mathematical modeling: Figure 3 shows a s implified schematic of the mirrors and the receiver tower from the front side. Significant parameters affecting the solar yield are d is the diameter of the receiver tube, n is the index and also the number of mirror strips on each side of receiver tower in one module, f is the focal height. The distance between center point of the receiver tube from the horizontal plane where bottom points of mirrors lie, W_n is the Width of the nth mirror, θ_n is the inclination angle of mirror measured counterclockwise from the horizontal plane, L_n is the distance of nth mirror's bottom end from the receiver tower, S_n is the Space between nth and (n-1)th mirrors, measured horizontally from last point of the mirror to the first point of next mirror, h_r is the horizontal position of receiver with respect to the origin, 0 is the origin of the module. Mirror's lower ends are positioned on the horizontal line which represents the x-axis for the calculations in following chapters. The receiver tower is aligned to the positive y-axis.

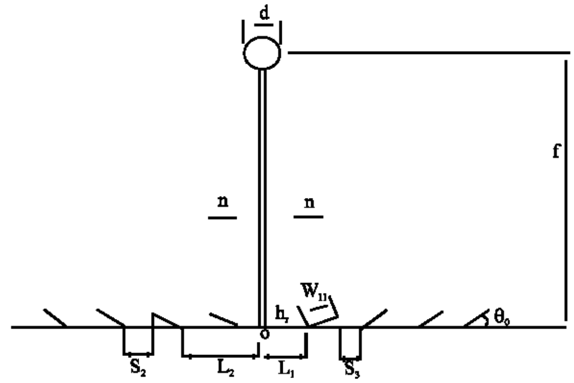

Fig. 3: Simplified schematic of the mirrors and the receiver tower

Building the mathematical model: For the modeling of the optical system only direct beam irradiance of the sun is considered. The concentrator-set of mirror strips populated on the platform is perfectly tracking the sun. Reflected Energy E_{ref} by the solar collector to the focal surface is a function of the incident solar Energy E_{in}, design, environment, and material parameters:

$$E_{ref} = f(E_{in}\text{design, environment, material}) \quad (1)$$

Reflected energy is basically equal to the incident energy multiplied by an efficiency factor η:

$$E_{ref} = \eta\times E_{in} \quad (2)$$

The energy initiating from the sun and reaching the receiver tube after being reflected by the mirrors is a function of incident solar energy on the mirrors, environmental effects and material properties of the mirrors. So, the reflected energy is proportional to the incident energy and multiplied by an efficiency factor. This efficiency factor η is also a function of the design, chosen materials and environmental effects:

$$\eta = f(\text{design,material,environment}) \quad (3)$$

The equation for the efficiency can be expressed as the multiplication of the efficiencies for the aforementioned factors design, material and environment:

$$\eta = \eta_{design} \times \eta_{material} \times \eta_{environment} \quad (4)$$

The efficiencies due to the material and environmental factors are not considered in this study. So, the design efficiency can be further divided in reflector and receiver efficiencies:

$$\eta_{design} = \eta_{reflector} \times \eta_{receiver} \quad (5)$$

The efficiency of reflector $\eta_{reflector}$ is a function of its physical dimensions and design where the parameters in following equation are stated before:

$$\eta\, \text{reflector} = f(W,\ f,\ \theta,\ S,\ L,\ d) \quad (6)$$

Following equations are used in iteration to find a mirror design for predetermined receiver diameter, width of mirrors and height of receiver where receiver is placed on the focal line of the mirror setup.

Following five equations are based on the study by Sootha and Negi (1994). In that study, the solar irradiation has been considered, so that, there is an angular subense of the sun on the earth.. In this study, the sun rays reaching the linear reflector system has been assumed to be parallel to each other.

Equation 7 calculates the inclination angle of the nth mirror. A vertical beam is drawn downwards to the end point of a mirror and reflected off the mirror to the receiver where it hits the lower half of the receiver tangentially. x_n and y_n are the coordinates of this tangential point. L_n is the horizontal distance of the nth mirror's lower point from the symmetry plane:

$$\theta_n = \frac{1}{2} \times \tan^{-1}\left(\frac{L_n + x_{a,n}}{y_{a,n}}\right) \quad (7)$$

Using simple trigonometric equities one will obtain Eq. 8 and 9 which provide the required values of the tangential point on the receiver tube to calculate the inclination angle θ_n of mirror strip:

$$x_{a,n} = R.\cos\theta_n \quad (8)$$

$$y_{a,n} = f - R.\cos\theta_n \quad (9)$$

To prevent the blocking and shading effects of mirrors to each other a minimum space-shift-should be kept between each mirror strip. Following equation calculates the required space between nth and (n-1)th mirror strips:

$$S_n = \frac{(L_{n-1} + W_{n-1}\cos\theta_{n-1}\square + x_{n,a})W\square_{n-1}\sin\theta_{n-1}}{y_{a,n}W_{n-1}\sin\theta_{n-1}} \quad (10)$$

Following Eq. 10 calculates where the lower end point of the mirror should be placed on horizontal plane which is required for installation. Namely this Eq. 10 defines location of the respective mirror. The width of the respective mirror strip, the shift and the location of previous mirror are required parameters:

$$L_n = L_{n-1} + W_{n-1}\cos\theta_{n-1} + S_n \quad (11)$$

Following Eq. 11 provide the factors to evaluate and compare the efficiency and functionality of the calculated mirror setup. The concentration factor defines the ratio of collected solar energy by mirrors to the concentrated energy on the receiver:

$$\text{Concentration factor} = \frac{Ar_{\text{mirror effective}}}{Ar_{\text{receiver}}} \quad (12)$$

The gross area of mirrors define the total area used for one side of the reflector including the sum of dead space -the necessary space between each mirror to prevent blocking and shading-between mirrors and sum of mirror's area on the horizontal plane:

$$Ar_{\text{mirror, gross}} = 2.\left[L_1 \sum_{n=1}^{k} W_n \cos\theta + S_n\right] \quad (13)$$

The effective mirror area is the sum of dead space between mirrors subtracted from the gross area of mirrors:

$$Ar_{\text{mirror effective}} = 2.\sum_{n=1}^{k} W_n \cos\theta \quad (14)$$

Area utilization factor is an important measure to determine how well the reflector area is used and how dense the mirrors are populated. A greater utilization factor allows greater reflection of incident solar energy to the receiver:

$$\text{Area utilization factor} = \frac{Ar_{\text{mirror effective}}}{Ar_{\text{mirror, gross}}} \quad (15)$$

Computational model: For the calculation of mirror setup, MATLAB and MS Excel is chosen. The equations mentioned above require to be computed in a loop. Given these conditions using MATLAB was the optimum choice.

To determine the positions of mirror elements in a Linear Fresnel Reflector (LFR) design, one needs to determine four main parameters.

- Width of the mirror element (W)
- Angle of inclination of each mirror element (θ)
- Respective distance of each mirror element to a reference point (L)
- Space between each mirror element (S)

Calculating the mirror setup: In order to determine these parameters Eq. 7-11 has been used. Equation 7 is used to calculate the inclination angle of each mirror strip and takes $x_{a,n}$ and $y_{a,n}$ as input. But then Eq. 8 and 9 which calculate $x_{a,n}$ and $y_{a,n}$, take θ_n as input. To solve this problem an iteration procedure should be performed. Firstly, a θ_n value is assumed and using this $x_{a,n}$ and $y_{a,n}$ are calculated. Then putting $x_{a,n}$ and $y_{a,n}$ in Eq. 7 gives another θ_n value. The θ_n values of this and previous steps are compared. So, the calculation should be put in a loop and iterated until the input θ_n to Eq. 8 and 9 and result θ_n of Eq. 7 matches. Following this, location of mirror strip and shift between mirrors are calculated.

The code first takes input values for d, f, W width of the LFR module on one side and minimum shift between each mirror i from the user. Then initialization of variables is done. After taking inputs and initializing variables the above mentioned loop is executed. The loop calculates as many mirrors as they would fit in a somewhat wider area than the given width of the LFR module. Another small loop checks the positions of the mirrors and determines which one is the last mirror strip that fits within the defined module width.

After having the mirror setup calculated and number of mirror strips determined, next step is to round the significant figures of the results of the inclination angle, mirror locations and shift between mirrors to manufacturing limits. In the last step, the code imports the number of mirror strips θ, L, S and W to an MS Excel file.

Model validation: To implement the theoretical calculated mirror setup in the simulation environment some assumptions had to be made. Four cases of solar altitude angles were chosen as point of interest such as:

Table 1: Comparison of calculated power with the simulation results

Solar altitude angles	Direct horizontal Beam radiation (Wm^{-2})	Energy model calculation (W)	Simulation tracepro (W)	Difference (%)
90°	546	24056	24053	<0.01
60°	488	21501	21491	<0.01
45°	411	18108	18091	<0.01
30°	285	10156	9227	9

- 90°
- 60°
- 45°
- 30°

Simulation environment is built up using three types of building blocks:

- A surface source representing sun
- Mirror strips
- Receiver tube

A computational method was used to check the power yield results obtained by ray tracing on a reference setup. The calculation was crosschecked with simulation of TracePro software and since the results were correlating it was reliable to continue with the next step, sensitivity analysis to structural errors.

Table 1 shows the comparison results. For most of the solar altitude angles in the design interval of the receiver, the calculation and simulation results match. At 30° one can observe a difference of 9%. The reason is that the receiver length is not enough to absorb all the reflected power at this solar altitude angle and the computational model was not powerful enough to consider the loss due to this factor.

RESULTS AND DISCUSSION

Figure 4a shows the power change with respect to the vertical change in position of the receiver. The initial design position of the receiver is taken as origin. Then simulation is performed by linearly increasing-decreasing the height of the receiver with 1cm intervals until the received power decreases at least by 30% at one of the solar altitude angles. Same procedure is repeated with four solar altitude angles. As a result vertical change in position of receiver should be between -4 and +5 cm to prevent power loss more than 10%.Considering the 4 m height of the receiver tower, 4-5 cm position change means an error allowance of 1% which should not be ignored and regarded during mechanical design and manufacturing process. Still, small vibrations due to external disturbances will not have a big effect on the solar yield from the mechanical point of view.

Figure 4b shows the power change with respect to the horizontal change in position of the receiver. Since, the mirror setup is symmetric with respect to the receiver

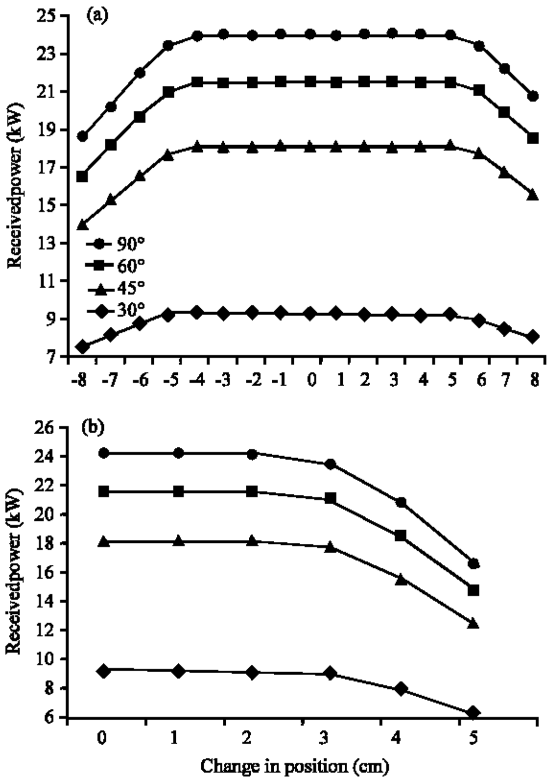

Fig. 4 a, b: Solar power vs. vertical and horizontal change in position of receiver, respectively

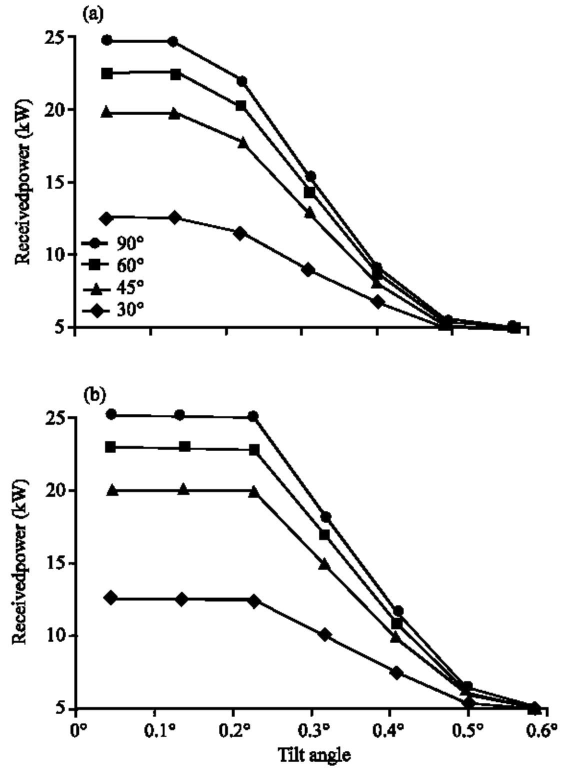

Fig. 5a, b: Solar power vs. angular smaller and greater inclination angles of mirror strips, respectively

tower, the change in position is considered only for one direction. The initial design position of the receiver is taken as origin. Then simulation is performed by horizontally moving the receiver to one side with 1cm intervals until the received power at one of the solar altitude angles drops to zero. Same procedure is repeated with four solar altitude angles. As a result horizontal change in position of receiver should be <3 cm to prevent power loss more than 10%.

The conclusion for Fig. 3 can also be deducted, here, that the receiver is not very sensitive to horizontal changes of position. Still the receiver is more sensitive to position changes in horizontal direction than vertical position changes. The significant drop in the solar yield is observed after 2 cm where for vertical change of position it started at 4 cm downwards and 5 cm upwards.

Figure 5a shows the change in received power by tilting the mirror strips in certain intervals and decreasing the inclination angle of mirror strips. The initial design position of the mirror strips are taken as origin. Then simulation is performed by decreasing the inclination angle of mirror strips with 0.1° intervals until the received power drops to zero. Same procedure is repeated with four solar altitude angles. As a result tilting the mirrors for smaller inclination angle should be less than 0.1° to prevent power loss more than 10%.

A possible solution to this problem can be to install a second stage reflector above the receiver tube facing downward towards the primary mirrors. Beside that the thermal drawbacks of the second stage reflector should be analyzed, since, the redirected sunrays will be hitting upper part of the receiver tube. In a DSG system if the receiver tube is not filled with water and there is two phase flow in the pipe, the gaseous part of the flow will be heated. That might cause structural defects on the receiver because of local overheated areas.

Figure 5b shows the change in received power by tilting the mirror strips in certain intervals and increasing the inclination angle of mirror strips. The initial design positions of the mirror strips are taken as origin. Then simulation is performed by increasing the inclination angle of mirror strips with 0.1° intervals until the received power drops to zero. Same procedure is repeated with four solar altitude angles. As a result tilting the mirrors for greater inclination angle should be <0.2° to prevent power loss more than 10%. Within this 0.2° error the mirror is still aiming mostly at the receiver. Beyond that, a dramatic drop is observed and the mirrors are defocused.

The conclusion for Fig. 5a can also be deducted ,here with an addition that the system is somewhat less sensitive for greater inclination angles. In this case, the missing rays are not hitting the receiver by going away from downside of it. Making the second stage reflector longer at the edges and introducing a little bit more curvature might lessen the effect of this problem.

Making a stronger and more stable mechanical platform structure remains also as a possible solution for all of the four aforementioned error types.

Figure 6 shows the change in received power when there is an error in tracking the azimuth angle of the sun. Sun being perfectly tracked was chosen as origin. Then simulation is performed by introducing an error to the azimuth angle tracking in 0.1° intervals until the received power drops to zero. Same procedure is repeated with four solar altitude angles. As a result tracking error should be <0.3° to prevent power loss more than 10%.

Sun tracking is a vital factor in every CSP system to obtain a high efficiency. Due to reflection geometry, the azimuth tracking error doesn't play a role on the solar yield when the solar altitude angle is 90°. Still for lower solar altitude angles, the effect gets more powerful. The preciseness of a tracking system is most of the time directly related with its costs. This figure provides an understanding for the level of preciseness required in such a LFR system.

Table 2 and 3 summarize the figures presented in this chapter. If the parameter changes are kept within the limits stated in Table 1, the loss in received power should be <1%. The factors are listed in decreasing order of importance. The inclination error of the mirrors has the greatest effect on the solar yield where the allowable error interval lies between 0.1° and 0.2° for a solar power yield loss <1 %.

Most of the energy loss due to sensitivity errors takes place at the outer mirrors. Main reason for this is that their inclination angles are relatively greater than the inner mirror which are near to the receiver and the reflected sun rays follows a shorter distance. These differences make the outer mirrors more vulnerable to external disturbances. Another notable point is that azimuth tracking error is the only error type that is affected by the solar altitude angle. Azimuth tracking error is also less effective by higher solar altitude angles.

A quick look will reveal that the angular changes affect the power yield at most. Even an increase of inclination angle errors by 0.1° causes a solar yield loss of up to 33%. The azimuth angle tracking has a comparable importance as well. One can conclude that angular stability has the uttermost importance to provide a stable solar yield from a LFR module.

The changes in position of the receiver in vertical or horizontal direction are not affecting the solar yield as much as the angular errors. This indicates that the LFR

Table 2: Maximum allowable parameter change to achieve < 1% change in the reflected power

		Solar altitude angle received power on the receiver (W)			
Affected factor	Error	90°	60°	45°	30°
Reference received power					
Mirrors	-	24053	21500	18097	9267
θ smaller	0.1°	24064	21502	18100	9221
θ greater	0.2°	23788	21256	17846	9118
Platform					
Azimuth tracking, (λ)	0.2°	24053	21466	18106	9040
Receiver					
Horizontal, (h_r)	±2 cm	24053	21491	18091	9218
Vertical (f)	-4 cm	24053	21491	18091	9312
	+5 cm	24049	21491	18091	9091

Table 3: Maximum allowable parameter change to achieve less than 33% change in the reflected power

		Solar altitude angle received power on the receiver (W)			
Affected factor	Error	90°	60°	45°	30°
Reference received power					
-	24053	21500	18097	9267	
Mirrors					
θ smaller	0.2°	20818	18600	15657	8009
θ greater	0.3°	16093	14381	12055	6259
Platform					
Azimuth tracking, (λ)	0.3°	24053	21459	18088	6879
Receiver					
Horizontal, h_r	±4 cm	20603	18418	15496	7773
Vertical, (f)	-8 cm	18431	16457	13860	7451
	+8 cm	20687	18464	15551	7927

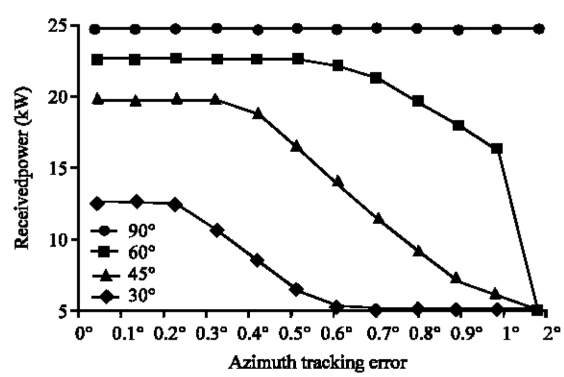

Fig. 6: Solar power vs. error of azimuth angle tracking

Fig. 7: Optical characterization of the LFR mirror at RAKRIC

module is not much affected by the environmental effects on the receiver tower such as wind and external vibrations, assuming that no angular disturbance is existent (Fig. 7).

CONCLUSION

Linear Fresnel reflector is a promising technology despite of its relative lower efficiency in comparison to other CSP technologies. Its low cost and easy manufacturability provides powerful advantages.

In this study, an equation model to generate a LFR mirror setup is built. Based on this equation model a LFR mirror setup is calculated and the calculated module's functionality is validated by in ray tracing simulation. Developing a mirror setup without blocking and shading has been accomplished.

After proving that the calculated mirror setup functions correctly, the existing LFR module of the RAK Research Center and the calculated LFR module are compared via. ray tracing simulation. The similar characteristics and solar yields of the modules allowed continuing with the sensitivity analysis on the existing module. This shift from calculated to existing module was necessary in order to enable a faster start of further experiments for future researches. Sensitivity analysis revealed that the solar yield is highly dependent on the angular accuracy of both mirror installation and azimuth tracking. The stability of receiver tower structure also has significant effects but not as crucially as angular stability. It has been also proved that the LFR system should be unaffected by small vibrations due to external disturbances such as wind, unless no angular error is introduced. In accordance to these before manufacturing the LFR module, manufacturing and installation error margins and preciseness should be considered thoroughly and measures should be taken, accordingly.

RECOMMENDATIONS

For future research, before continuing with experimental research it is suggested to conduct a research on thermal behavior of the receiver tube and the fluid in it. Only then the results can be used to build a reliable experimental setup and a realistic overall efficiency for the whole LFR module can be calculated. Since, research and engineering are iterative processes also in advance this study might need to be updated in light of these future results. This research led to the optical characterization of the LFR mirror at the RAK Research and Innovation Center.

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