Optical Characteristics of Glass Mirror Reflector for off-axis Concentrators: A Ray-Tracing Approach

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Abstract

Less acceptance and penetration of solar concentrating technology due to its high cost has inspired the research for alternative low-tech technologies and reflecting-materials. This paper aims to model and experimentally investigate optical characteristics of cost effective reflecting-materials on low-tech concentrators, which are easily available in the local market for wide low to medium temperature applications. Ray-tracing methods were employed to model and adjust the solar-concentrator position and geometry of reflecting-material. From the ray-tracing simulation, optimum glass mirror sizes of 1.5cm, 3cm, 4.5cm, and 6cm were selected to be tested at the optimum tracking position. Validation of the model was done by artificial laser-beam and ground radiation tests. Results gathered from the simulation and experimental tests were in a number of rays received and reflected back as well as temperature level at the focal point. The study from the simulation and laser beam test yields intercept ratio varied from 56.06% to 51.4% and 51.21% to 45.61% respectively. The respective results from the thermal test range between 52% and 31%. These results together with the observed image sizes indicate that the use of small sized glass mirror reflector at 00 incidence angle best fits the curvature of low-tech off-axis concentrator and attains higher efficiency.

Keywords: Image, Intercept ratio, Mirror facet, Ray-tracing, Solar-concentrator

1. Introduction

Various solar thermal concentrators (STC) have been widely used to collect solar radiation and convert it into high temperature heat using heat transfer medium. The main types of STC are stationary concentrating collectors (non-imaging concentrators), parabolic trough, linear Fresnel with mirror or lens, parabolic dish, and power tower. The STC consists of mainly two components, as reflector and receiver (Senthil et al. 2017). The high reflective, low absorptive, and low transmissive properties of the reflector are important for solar concentrating surfaces (Pavlovic et al. 2015).

The solar reflector designs are almost matured at this stage due to the exhaustive studies on the mirror and highly polished or coated metal surfaces (Arancibia-bulnes et al. 2017). From the several optical materials investigated as reflectors for STC, a parabolic mirror is the ideal optical configuration for solar parabolic thermal concentrators. However, the fabrication of parabolic mirror is very expensive and its cost increases rapidly with increase of aperture area (Pavlovic et al. 2015). Thus, the use of commonly available or recycled materials as the solar reflector in low-tech parabolic dish is assumed to be cost-effective in future reflector designs.

Analytical, optical, and experimental methods are used to study the characteristics of solar concentrators and receivers. Ali et al. (Saleh et al. 2013) have demonstrated the use of ray-tracing software to predict the optical performance of a static 3-D Elliptical Hyperboloid Concentrator (EHC). The concentrator profile and geometry optimization was carried out to improve overall system performance. Pujol-Nadal et al. (Pujol-Nadal et al. 2015) characterizes solar concentrators by combining both ray-tracing tool and thermal experimentation in the field.

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Coefficients of energy, optical, and thermal efficiency were determined at normal incidence angle. Rafeeu et al. (Rafeeu and Kadir 2012) have introduced simple procedures for design, construction, and test of small laboratory scale parabolic concentrators. Three experimental models with different geometrical features were used to examine the geometry effect on solar radiation concentration. Using ray-tracing tool to determine an appropriate geometry, José Ruelas et al. (Ruelas, Palomares, and Pando 2015) studied concentrating capacity of Stirling engine coupled Scheffler type solar concentrator. Validation of the focal image-geometry from ray-tracing was executed by visualizing thermo-graphic images of the concentrators. Zhiqiang et al. (Liu, Lapp, and Lipiński 2012) designed mirror facets for a parabolic concentrator. Ray-tracing tool was used to optimize size and shape of mirror facets. In addition to positioning of mirror facets, flux density was analysed by applying Monte Carlo ray-tracing method. Aránzazu et al. (Fernández-García et al. 2017) investigated an optical characterization of solar reflectors using ray-tracer tool. Literatures were reviewed and discussed for different ways of measuring reflector materials performance and creating reflectance models.

The primary significance of ray-tracing simulation is that it is quite simple to compute shadows and reflections. However, the main limitations are assuming radiation source as a uniform disk with equal power and perfect alignment of reflecting surface on the curvature of solar-concentrator (Bode, Gauché, and Griffith 2014). The significance of different aspects of experiment following simulation is, therefore, to predict the optical efficiency considering misalignments and sensitivities that enable validation of the model (Aguilar et al. 2014). Such studies are used to predict the performance of solar-concentrator at different operating conditions and reflector designs. The optical characteristics depend on the number and geometry of focal image as well as the temperature level of the receiver. In general, efficient reflection has a high concentration of irradiation and low absorption of heat radiation.

The study aims at optimization and comparison of multi-size tiled glass mirror facets in addition to positioning of the solar-concentrator. It envisages achieving low to medium temperature for typical domestic applications using locally available low-tech concentrator and reflector. To achieve the objectives of the study, quantitative and qualitative analysis are implemented. Offset parabola calculator, Simsun target ray-tracer, and different optical and thermal tests that determine and validate the optical characteristics of the reflecting facets are used. Through the implementation of recommended materials and construction measures, the study will have significant importance in promoting low-tech and cost-effective STC.

2. Materials and Methods

2.1. Description of the STC

In this study off-axis type parabolic dish concentrator with a large diameter of 90cm, smaller diameter of 82cm, and depth of 7cm were used. As the feed is positioned outside the area of the beam, the purpose of this design was to increase the aperture efficiency of the receiver by increasing its gain. It is also due to the less curved parabolic shape that has the possibility of using cost-effective crystal type reflectors.

Glass mirror with reflectivity up to 0.88 were selected as a reflecting-material depending on its cost and availability. Glass mirrors have good durability in terms of reflective layer corrosion. The big limitation of using glass mirrors is their none-flexible physical property. Since these glass mirrors are crystal in structure, it is very difficult to have a big curved parabolic shape (García-Segura et al. 2016)(Sark et al. 2008). Flat steel sheet metal covered by a thin coat of black paint having absorption coefficient close to 0.9 was placed in the focal area (Pavlovic et al. 2015)(García-Segura et al. 2016).

2.2. Geometric Design

Parabola calculator portable 2.0 Freeware program was used to calculate the focal length, arc length, aperture area, and rim angle of the specified solar-concentrator. The geometric concentration ratio is defined as the effective area of the concentrator aperture divided by the area of the receiver (Ngo 2012)(Eccher et al. 2013). This can be given as:

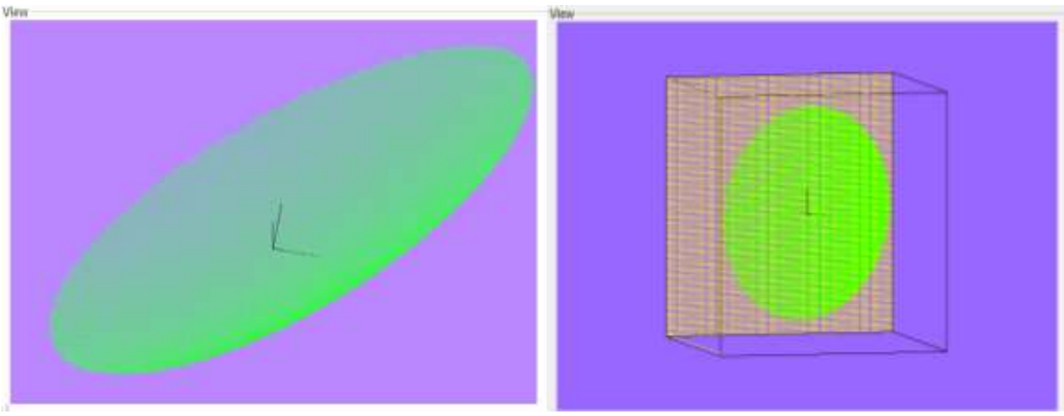
$$C_g = \frac{A_a}{A_r}, \qquad A_a = \pi R^2, \qquad A_r = \frac{\pi}{4} d^2 \tag{1}$$

Where A_a is aperture area of the parabolic dish, A_r is receiver area, R is radius of parabolic dish, d is diameter of receiver.

2.3. Ray-tracing Modeling

The geometry of the solar-concentrator was modeled to scale in Simsun target ray-tracing tool. The sun and boundary box within the modeled solar-concentrator are placed to carry on the ray-tracing simulation. The sun is user-defined and the boundary box is fixed to the size of the sun. Sun points of 100cmx100cm on a square grid are used to cover the diameter (90cm) of the dish. The surface of the solar-concentrator was covered with multi-size tiled crystal structure (glass mirror). Tracking system is the most important condition in solar concentrating system, since the sun tilts. On Simsun target ray-tracing tool it is possible to rotate the sun or the dish. Tilt angle in each hour as well as yearly minimum and maximum angle and position of the sun was chosen. Sun rotation is chosen at every 15º and the parabolic dish is at a fixed position. After all, rays towards the reflector were simulated to get a result in quantities of rays reflected back to the focal area (Nydal 2014).

The models were created by selecting the type of concentrators and absorbers at the taskbar depending on the objective of the simulation. Below the taskbar there were input dimension pads, which enabled to insert the dimensions to the specified reflector or receiver (Nydal 2014)(Ruelas et al. 2014). The modeled objects are displayed in the view workbench as shown in Figure 1.



(a) (b)

Figure 1: Simsun software models (a) Reflector integrated dish (b) Boundary box, reflector integrated dish, and sun

The next step was tracing the rays towards the model depending on the tracing options and other control buttons. Finally, the numbers of rays released and reflected were displayed on the result pad to determine the intercept factor (Nydal 2014)(Ruelas et al. 2014).

In this study, the academic version Simsun target ray-tracing software was used to determine the intercept factor for the given concentrator position and reflector sizes. Depending on the input parameters, the Simsun target ray-tracing optimizes the concentrator position and reflector size. The main equation in the software is the law of specular reflection and it uses forward sequential ray-tracing approach. The computational method of the software is Monte Carlo ray tracing. The main limitation of the software is that it assumes all rays incoming from the sun have equal amount of power despite the fact that power depends on the wavelength and solar radiant power which is distributed between 0.3μm to 3μm of the electromagnetic spectrum. In optical engineering, the error introduced by such assumption is considered to be very small and the optical efficiency mainly depends on facet spatial shape, alignment and a total number of rays released and reflected (Nydal 2014)(Ruelas et al. 2014).

2.4. Experimental Setup and Instrumentation

To study and validate the simulation results, practical integration of multi-size tiled mirrors were done. Based on the simulation output, four sizes of tiled mirrors were selected at 1.5cm interval for comparison. Ray-tracing simulation was followed by validation in two aspects of experiment. While conducting indoor artificial laser beam tests, rays were released to the prepared solar-concentrator through a grid structure apparatus. The outdoor test were carried out on March 28, 2018 using solar radiation in Mekelle, Ethiopia (latitude: 13° 28' 31.19" N, longitude: 39° 29' 9.59" E, altitude: 2208m) (Mahmud et al. 2014)(Kahsay et al. 2014).

Appropriate size of square shaped tiled glass mirror was cut using a small cutting wheel 5 mm in diameter made of hardened steel with a 120° V - shaped profile. Essentially, as small size mirror could be broken, preparing mirror size bigger than one cm is recommended (Fernández-García et al. 2017). Once the facet is cut to size, assembling is the easiest task but may take a long time and require accuracy (Ren et al. 2014). Glass mirrors were mounted to attain the curvature of the dish by the procedures in Figure 2 (a ,b).

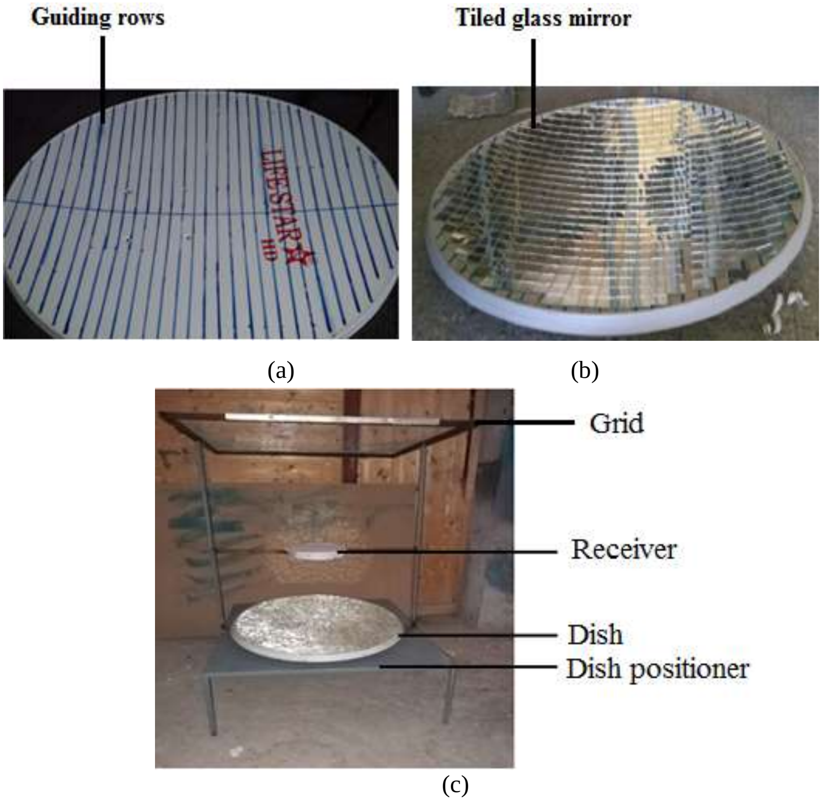


Figure 2: Assembling procedures of glass mirror facets on the parabolic dish (a) Drawing the row guidelines on the dish (b) Mounting the mirror on the specified dish with glue (c) Artificial laser beam ray tracer apparatus

Equal sized parabolic dishes with different tile size glass mirrors were prepared to be tested under the two experiments. Following this, simple experimental setups were developed. In manual laser beam ray tracing structure (Figure 2 (c)), there are grids to guide the laser beam from the top side. The parabolic dish integrated with different sized glass mirrors and aluminum foil was kept below the grid at the dish poisoner. The principle is similar to how the Simsun software works but with a different way of releasing artificial laser beam.

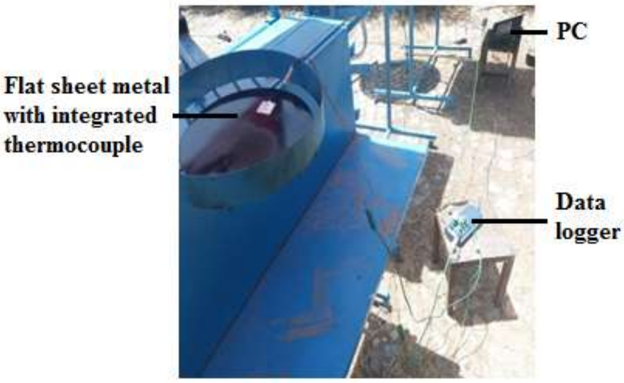
In doing this, the artificial beam focused on the receiver through each grid one by one were marked and counted to determine the intercept factor. The intercept factor (γ) is expressed as a quotient of the rays intercepted by the receiver (Duffie 2013). This can be given as:

$$\gamma = \frac{n_{total\ number\ of\ rays\ received\ on\ the\ concentrator}}{n_{number\ of\ rays\ reflected\ to\ the\ focal\ region}} \quad (2)$$

The experimental tests described above, to count the number of rays and observe image size of the reflected rays. Regarding to this observations, the issue was determining: whether the glass property, the surface geometry, and the wave length of incoming ray greatly impact the collector efficiency or not.

To address the concern, additional experiment to test the thermal performance of the solar-concentrator model without load were designed and conducted. For the performance test, simple structure was developed as shown in Figure 3. The test setup adjusts k-type thermocouples in the place where the temperature reading is needed, such as the surface of the receiver. The thermocouple is made of +/- conductors of Nickel Chromium/Nickel Aluminum with a sensitivity of -200 to 1250 ^{0}C. The accuracy of the thermocouple is ± 0.18%. The temperature of the experimental period was logged using PicoLog Technology TC-08 with an accuracy ± 0.5%. The solar radiation was measured by connecting SPN1 sunshine Pyranometer sensor with an accuracy of +/-5% to a GP1 data logger in order to convert the voltage signal to an equivalent reading in W/m^2. It is then connected to a laptop computer where the data was recorded and saved in order to get the reading of temperature for every 10 minutes. .

(a)



(b)

(c)

Figure 3: Thermal performance test setup (a) Apparatus (b) Instrumentation (c) Tracking method

As the sun tilts every 10 - 15 minutes, tracking was done manually by moving the support structure to the sun's direction, maintaining the center of the circular shadow of the parabolic dish under the support structure as shown in Figure 3 (c).

Performance analysis using steady state heat balance of the receiver and reflector was made. This determined the characteristics of the solar-concentrator such as the collector efficiency using equations 3.

$$\eta_{col} = \eta_{opt} I_a A_a = m_r C_p (T_f - T_i) \quad (3)$$

Where η_{con} is collector thermal efficiency, η_{opt} is concentrator optical efficiency, I_a is insolation incident on the concentrator aperture, A_a is aperture area, m_r is mass of receiver, C_p is specific heat capacity T_f is final temperature of receiver, T_i is initial temperature of receiver (Duffie 2013).

The thermal efficiency is directly related to the optical efficiency and the useful heat. In turn, the useful heat is related directly to the temperature of the receiver at a given time.

The equations to estimate the optical efficiency are given as:

$$\eta_{opt} = \rho \tau \alpha \gamma [1 - A_f \tan(\theta) \cos(\theta)] \quad (4)$$

$$\eta_{opt} = \frac{C_o}{C_g}, \quad C_o = \frac{S_o}{S_a} \quad (5)$$

Where ρ is reflectance, τ is transmittance, α is absorptance, γ is intercept factor, A_f is geometric factor, θ is angle of incidence, C_o is optical concentration ratio, C_g is geometric concentration ratio, S_o is cross sectional area of parabolic dish, S_a is the lighted area of the receiver (Ngo 2012)(Eccher et al. 2013)(Duffie 2013).

The optical efficiency is related directly to γ and inversely to S_a; these are the most complex parameters involved in determining the optical efficiency. Thus, in determining γ, the temperature of the receiver for a specified time was measured. The S_a was measured qualitatively looking in to the size of the marked image from the indoor and outdoor tests . In addition, the brightness on the receiver was used as a qualitative measure of optical efficiency.

3. Results and Discussions

The geometric concentrator and receiver parameters identified by the parabola calculator and geometric design analysis are summarized in Table 1.

Table 1: The geometric design values of parabolic dish and receiver

Focal length [m]	0.72
Aperture area [m^2]	0.64
Dish rim angle [^{0}]	0.80
Arc length [m]	1.27
Concentration ratio (C_g)	20.25
Receiver diameter [m]	0.02
Receiver area [m^2]	0.0314

Using the geometrical parameters obtained for the collector, the effect of position on the performance of the concentrator shown in Figure 4 indicate the need for continues or an interrupted tracking mechanism.

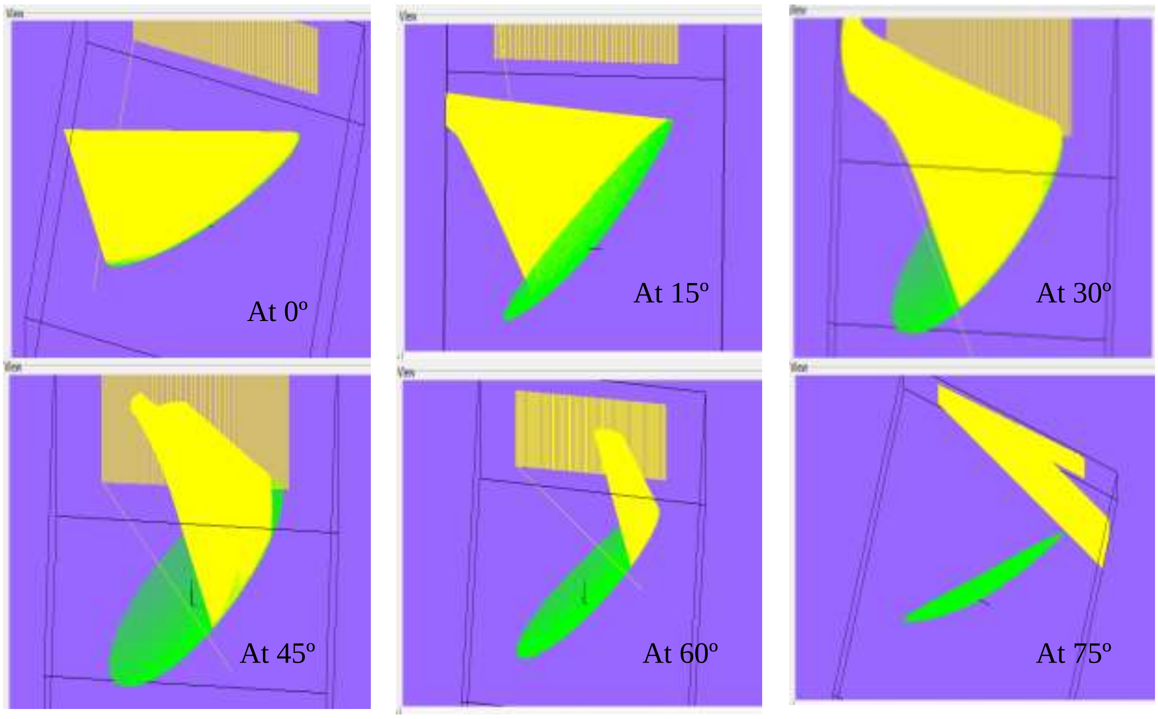


Figure 4: **Effects of solar tracking mechanism with tilting sun (view workbench)**

The smallest possible tile size (mirror facet of 1cm x 1cm) showed 5664 hits out of 10000 incoming rays at the receiver as depicted in Figure 5. Similar simulations for the intercept factor against different mirror facet sizes showed a decreasing trend (Figure 5), the intercept factor gradually decreases for small sized tiles and drops sharply for larger sized tiles between 0.08m and 0.09m. Once it covers the upper diameter of the parabolic dish the intercept factor becomes constant.

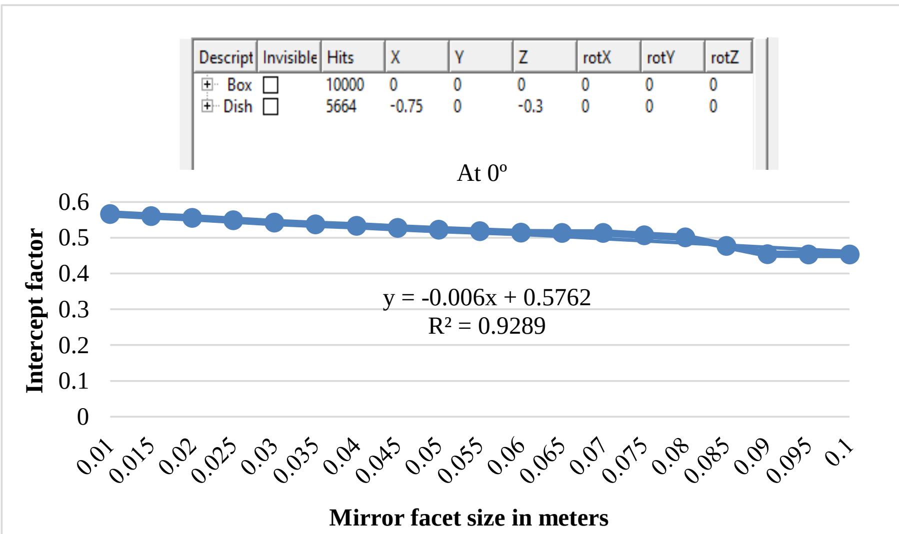


Figure 5: **Glass mirror facets versus intercept ratio**

For comparison, counts of the rays for all samples of the mirror tile from Simsun simulation and laser beam experiment are shown in Table 2. In general, both the Simsun simulation and laser beam test showed a decreasing trend of the intercept factor/optical efficiency. Also, lower values were observed by laser beam test relative to the estimated results by Simsun simulation. However, the experimental test reveal 4.5 cm mirror facet attains lowest error. This is could be mainly due to its best reflector alignment (fit).

Table 2: Ray-tracing results from simulation software and laser beam test

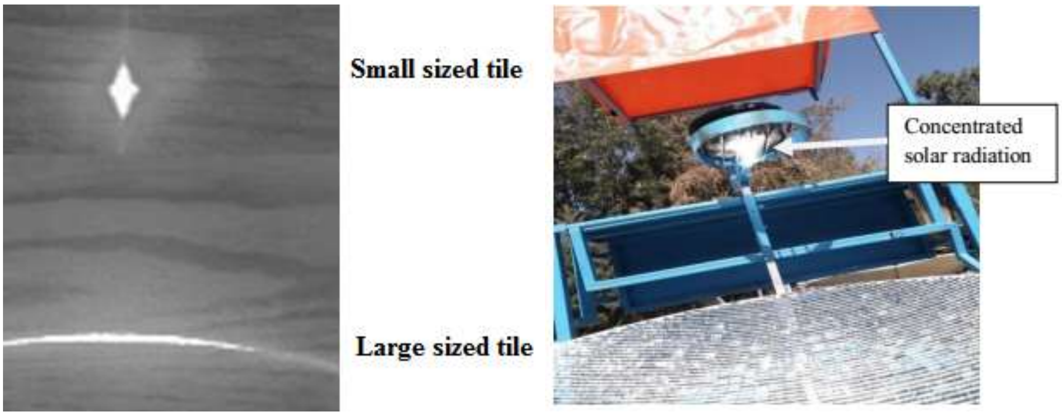
Reflector	No. of rays received	No. of rays reflected (Sim.)	No. of rays reflected (Test)	Intercept Ratio (Sim.)	Intercept Ratio (Test)	Error
1.5 cm mirror facet	10, 000	5, 552	5, 121	0.5606	0.5121	0.0485
3.0 cm mirror facet	10, 000	5, 424	4, 978	0.5424	0.4878	0.0546
4.5 cm mirror facet	10, 000	5, 226	4, 754	0.5226	0.4754	0.0472
6.0 cm mirror facet	10, 000	5, 140	4, 561	0.5140	0.4561	0.0579

To see the effect of beam strength (wave length), the receiver surface temperature after 30 minutes for all samples were measured as presented in Table 3. The corresponding thermal and optical analysis showed the general decreasing trend and higher deviation from Simsun results of intercept factor for large sized tile mirrors.

Table 3: Results from thermal performance test

Reflector	Surface Temperature in 30 min (^{0}C)	Intercept Ratio
1.5 cm mirror facet	157.17	0.52
3.0 cm mirror facet	127.13	0.35
4.5 cm mirror facet	125.78	0.33
6.0 cm mirror facet	119.20	0.31

The glass mirrors with small tile size were observed to reflect the laser beam and solar radiation on a smaller area compared to the large tile size glass mirrors. The image sizes of small and large tile size mirrors using laser beam are shown in Figure 6 (a). While conducting the thermal performance test, the concentrated solar radiation on the bottom surface of the receiver is depicted in Figure 6 (b). The glass mirrors with small tile size are observed to have relatively brighter light at the receiver. Knowing rays reflected on smaller area and half of the solar radiant energy is contained in the visible region, this was a good qualitative confirmation for the concentration characteristics of the reflecting materials.



(a) (b)

Figure 6: Light image (a) artificial laser beam (b) solar radiation

Overall, there were two distinct observations from the comparisons. First, the initial collector model predicted higher collector efficiency than the measurements. This discrepancy was created mainly due to the tile size of the reflecting surface for the mirror facet. The effect is apparently much higher for large size tiles significantly impacting the concentrator intercept factor, decreased to 0.31 from 0.514. The other inconsistency for 4.5 cm tile mirror facet was created due to its best parabolic alignment. Relatively small error was observed 0.0472. After the geometric factor for large tile sized mirrors and the curvature fit adjustment, the deviation between the experimental data and the model could be minimized for the initial solar-concentrator model. This is result in agreement with Nydal et al. (Nydal 2014) study that showed two sensitivities of the reflectors, as smooth and tiled. The study demonstrated the preference of small sized tile to get higher temperature result.

4. Conclusions

The aim of this paper was to demonstrate the use of low-tech concentrator and cost-effective reflectors, which are easily available in the market, for wide low to medium temperature applications. Results gathered from the Simsun simulation nd and laser beam test showed a higher intercept ratio of 56.06% and 51.21% for the small sized (1.5cm) glass mirrors. The outdoor test came up with a higher receiver temperature of 157.17^{0}C and corresponding 52% intercept ratio for the small sized glass mirrors. These values together with the qualitative observations on reflected image size, resulted in higher concentration of the off-axis parabolic dish using small sized glass mirror tiles.

Further updates are possible in the Simsun simulation model according to the requirements. It can be useful and be improved by subjecting it to detailed experiments on effects of misalignments while assembling and other manufacturing and operation sensitivities as well as beam strength, which are very difficult to quantify numerically. The methodology developed can be applied for such actual working models.

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