Prediction of Focal Image for Solar Parabolic Dish Concentrator With Square Facets – An Analytical Model

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Research Article

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Posted Date: December 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1067854/v1

Prediction of Focal Image for Solar Parabolic Dish Concentrator with Square Facets – An Analytical Model

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Abstract

Solar parabolic dish concentrator is one of the high-temperature applications of more than 400 °C for thermal and electrical power generation. In the solar parabolic dish concentrator, the arrangement of reflectors over the surface area is the significant factor for effective concentration of solar radiation. Also, focal image is one of the most influencing parameters in the design of receiver. Among the various reflectors, the square shaped reflectors (facets) are comparatively effective in converging the incoming radiations to attain better focal image. In this regard, an attempt has been made to predict the focal image diameter of a solar parabolic dish concentrator with a square facet of different influencing parameters using a novel mathematical model. The influencing parameters considered for the study are aperture diameter, rim angle, and facet length of the dish concentrator. Based on the proposed model, the focal image dimension and aperture area of a solar parabolic dish concentrator with square facets can be predicted accurately for efficient design of a solar parabolic dish collector system. Finally, the proposed model is validated with the experimentally obtained focal image diameter and it is observed that the predicted result is in good agreement with the experimental one. Thus, the proposed model can be effectively used for the design of parabolic dish system for sustainable development.

Keywords: Paraboloid dish concentrator; square facet; focal image; confocal parameter; fringe size.

Nomenclature

d	diameter of the solar image
f	focal length of the parabolic dish
D	rim diameter of the parabolic dish
L	length of a facet
y	depth of parabola
x’	horizontal width of dish exposed to solar radiation
f_1, f_2	Intersection point of extreme reflected rays at the axis of the parabola
f*	Actual solar image location from the apex

Greek symbols

ω_o	half conical angle (0.266°)
ϕ	rim angle of the parabolic dish
α	horizontal inclination of facet at the extreme
ρ_1	horizontal inclination of reflected ray at point (x_1, y_1)
ρ_2	horizontal inclination of reflected ray at point (x_2, y_2)

1 Introduction

Energy is introduced as an essential measure for the all-around development of the nation although green energy systems are considered essential for the sustainable development of the nation and the world. As the world is encountering a huge rise in the populace, conventional energy resources are nearly getting drained. In this situation, the world is moving towards non-conventional energy resources like solar energy, wind energy, geothermal energy, salinity gradient power, and so on (Østergaard et al. 2020). The non-conventional energy resources, solar energy is the most dominating and remarkable source of energy. The sun is a classic source of energy that can satisfy the power needs of the whole earth. In contrast to other fossil fuels, the sun is a limitless source of energy which is a critical hotspot in the future for clean energy. The fundamental limitations of using solar power are more investment costs and accessibility of less efficient power transformation technologies.

Even though there exists a great deal of solar power transformation innovations accessible, the concentrating solar power (CSP) technology draws in numerous researchers because of the capacity of producing heat at a higher temperature. The concentrated solar parabolic dish (CSPD) collector system is one of the CSP developments which concentrates the solar radiation to the most significant among the accessible inventions and is generally competent among the available concentrated collectors (Kalogirou 2009). CSPD technology has numerous applications where high temperature is required, for example, steam generation, pyrolysis process, thermionic fluid heating for process heat applications, thermal energy storage systems, power generation using Stirling engine, thermoelectric generators, concentrating photovoltaic, and so on. Aside, the capital expense of the CSPD collector system is exceptionally high which is a significant barrier for commercialization (S P Sukhatme and Nayak 2017). Hafez et al. have reviewed the design analysis factors of a solar parabolic dish for different applications and performed a simulation of a solar parabolic dish with Stirling engine applications to determine the efficiency and power outcome of the system (Hafez et al. 2016, 2017). Jian et al. proposed a novel optimization method for the uniform distribution of solar flux in a cavity receiver of a solar parabolic dish concentrator system (Yan et al. 2018). Premjit and Reddy investigated the flux distribution at the focal plane of a square solar parabolic dish concentrator for concentrating photovoltaic application (Singh and Reddy 2020). Lan et al. performed an optical simulation for determining the performance of a cylindrical cavity receiver for a solar parabolic dish system (Xiao et al. 2020). Using a 4 m aperture diameter parabolic dish concentrator, Sahu et al. investigated a flat receiver with a double trumpet shaped secondary reflector. In the parabolic dish, a square mirror facet was used as a reflector element (Sahu et al. 2021).

Researchers have discovered fabrication of double-curved reflector panels are expensive and requests advanced fabrication procedure, and subsequently thought of planar facets because of ease of fabrication (Toygar et al. 2016). Although this process is affordable, the heat output is not sufficient because of the lack of established relations to appraise the exact solar image. Lifang Li and Steven Dubowsky proposed another method for fabricating the solar parabolic dish concentrators using flexible petals with optimum parameters. A numerical study was led for the structure and an experimental study was performed with a prototype under the solar simulator. Guaranteed that the proposed method will give exact solar parabolic dish collector and minimal cost than the conventional method (Li and Dubowsky 2011). Researchers have attempted experiments to decide the optimal solar image size and location. Pavlovic et al. led a ray-tracing simulation study to determine the optical characteristics of the sun image size (Pavlovic´ et al. 2014). Sainath and Nitin performed a ray-tracing simulation to study the possibilities of the reflector position and shape for a compound parabolic dish concentrator. Though ray tracing simulation which is a numerical method available for the prediction of solar images the current paper developed an analytical model for the determination of solar parabolic dish concentrator parameters (Waghmare and Gulhane 2019). To estimate the distance between the concentrator and the receiver, Pavlovic et al. performed optimization research on the parabolic dish concentrator with trapezoidal reflective pads (Pavlović et al. 2016). Liu et al. proposed a new method by optimizing the size and placement of square facets in a solar parabolic dish concentrator (Liu et al. 2012), Farouk et al. used the ray tracing technique to investigate the optical performance of inverted absorber line axis compound parabolic concentrating solar collectors and published their findings in terms of receiver height (Farouk Kothdiwala et al. 1996).

Wen et al. gave the geometrical optic relations to find the fringe diameter of a solar image for an ideal parabolic dish concentrator (Wen et al. 1980). Afterward, Kaushika added an error to the conical angle which occurred due to imperfections in optics and gave the solar image size for finding a multifaceted solar parabolic dish concentrator (Kaushika 1993). This proposed analytical relation depended on the facet size and incident angle. It is being utilized as the formula to decide the solar image size for the CSPD concentrator with facets. Researchers used this relation to decide the fringe dimension for multiple applications (Hafez et al. 2017). Nonetheless, the relation just connotes on the fringe dimension alone without mulling over its location. To find the exact solar image location with more concentration ratio further computation needs to be done resulting in an effective receiver for the respective parabolic dish concentrator. The computation is focused on deciding the solar image with exactness and dependability for various facet lengths with varied parabolic profiles by geometrical analysis through computer-aided simulations.

As seen from the aforementioned literature review, the focal image of the parabolic dish concentrator is investigated as an important parameter for improving the total performance of the solar system. Consequently, the main novelty of this study is to determine the actual solar image size and its location for a solar parabolic dish concentrator with square facets as reflector elements using a new mathematical method. It should be mentioned that graphical methods show that the existing relations leads to huge error and does not result in optimum solar image location and dimension. The study takes into consideration the available facet size, conical angle of solar rays as well as the other parameters of the dish.

2 Modeling and Methods

In the present work, an analytical model for finding the solar image dimension for a parabolic dish concentrator using square facets was developed. Among the various reflectors, double curved facets are more effective in converging the incoming radiations on the focal plane. However, the fabrication of double-curved facets with high accuracy is complicated, expensive, and demands high skilled fabrication. As a better alternative, square planar facets can be selected. Nevertheless, the features of square facets of appropriate dimensions are almost similar to double planar facets with a minimum a deviation in flux distribution and focal image size. However, these deviations can be compensated with the economic feasibility and ease of fabrication of square facets. In this regard, the proposed method will provide a solution considering two cases: (i) the incoming solar radiations as parallel rays. (ii) the conical angle possessed by the solar radiations. As a final part, studying the shift in solar image position, the exact solar image location is concluded.

2.1 General concepts

The actual solar image border is defined by the radiations which are reflected by the rim elements of the parabolic dish; hence the rim facet elements are considered for the derivation part. It is necessary to determine the endpoints of the facets to determine the normal of the surface. The diameter and rim angle shown in Figure 1 gets the extreme coordinates ((x1, y1) & (-x1, y1)) of the parabola. The rim facets have been created with the given length (L) at the extreme coordinates of the parabola, where the second endpoint of facet P_2 (x_2 & y_2) can be acquired from the relations below.

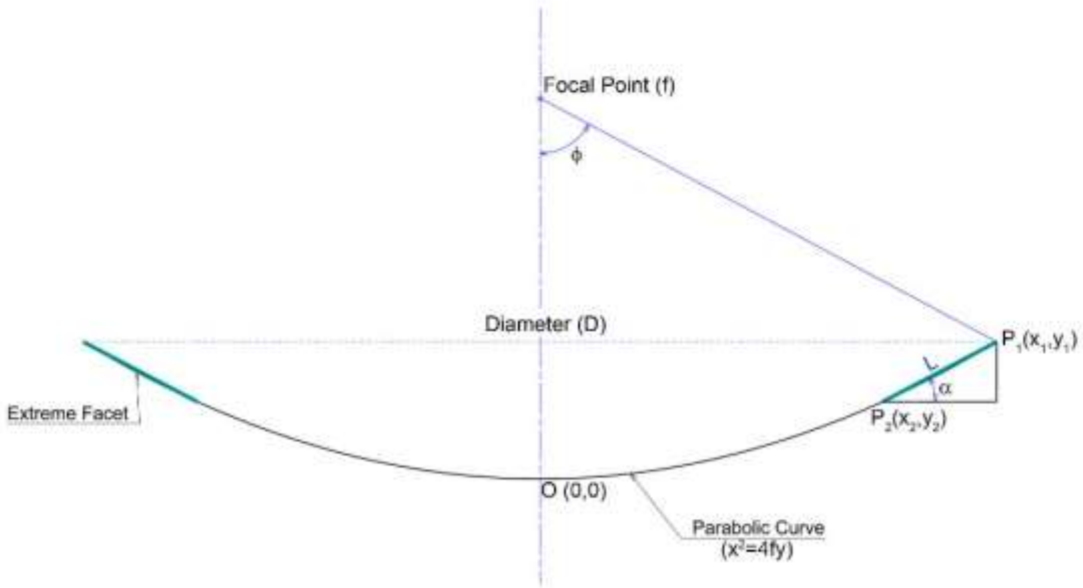

Figure 1: Parabolic dish with placement of facets at the extreme end

Equation of Parabola (Pavlovic and Stefanovic 2015) :

$$x^2 = 4fy \qquad \text{(Explicit form)} \qquad (1)$$

$$x = 2fu; \;\; y = fu^2 \qquad \text{(Parametric form)} \qquad (2)$$

The extremities of a parabola can be found by the following expression

$$x_1 = \frac{d}{2} \;\; ; \qquad y_1 = \frac{d^2}{16f} \qquad (3)$$

Solving for the facet length using linear equation the following simplified quadratic equation

$$k^4 - 4u_1k^3 + 4u_1^2k^2 + 4k^2 - \frac{L^2}{f^2} = 0 \text{ ; where, } k = u_1 - u_2 \qquad (4)$$

From the roots of the quadratic equation (eqn. 4), the coordinates of the facet end points can be determined.

2.2 Solar image diameter for parallel incident rays to the axis

In a parabolic dish, the solar image boundary is formed by the reflected rays at the extreme points and the same is observed in computer-aided graphical simulation. Thus, for deriving the fringe diameter of the solar image, the extreme facets and the reflections at the ends of the facet are taken. The intersection points of these reflections form the optimum solar image with maximum concentration ratio as demonstrated in Figure 2.

Two normal lines are created at points P_1 and P_2, endpoints of the extreme facet. The reflected rays for the incident vertical rays are obtained by Snell's law of reflection (angle of incidence with the normal is equal to the angle of reflection with the normal) (Kingslake and Barry Johnson 2010) as shown in Figure 2. The line AA' joining the intersection of the extreme reflected rays gives the solar image.

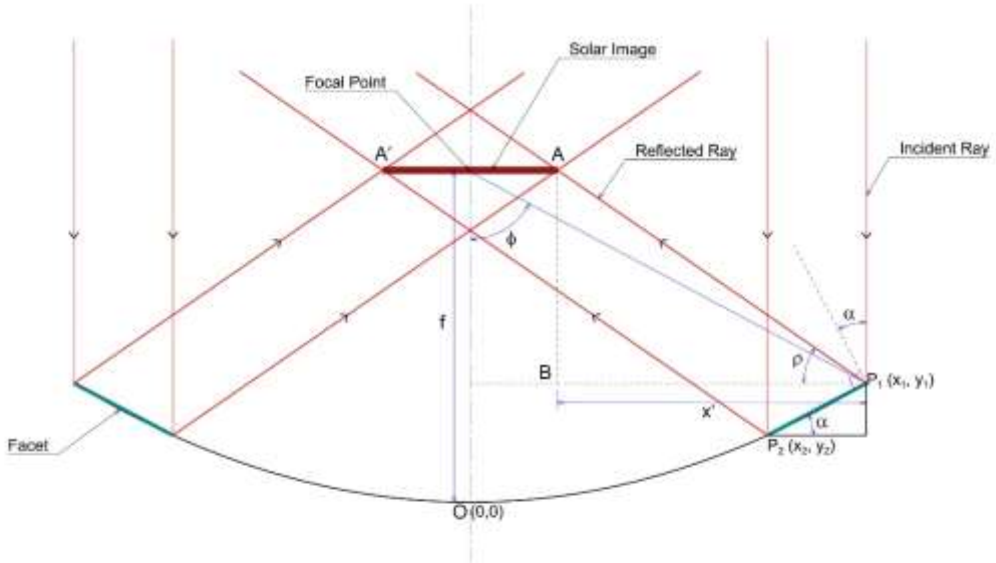

Figure 2: Solar Image formation of a parabolic dish concentrator with facets considering the solar rays as parallel.

From Figure 2, based on trigonometric law, the expression for x' can be given as below.

$$x' = \frac{f - y_1}{\tan(90 - 2\alpha)} \tag{5}$$

Hence, using the following expression (6), the solar image diameter of a solar parabolic dish concentrator with a square flat facet can be determined for the case, considering the solar rays as parallel.

$$d = D - 2x' \tag{6}$$

The validation of the derived expression was conducted and from the obtained results, it was evident that the proposed model matches exactly with the geometrical simulation model.

2.3 Solar image diameter considering the conical angle

In the previous case, the radiations coming from the sun are assumed to be parallel. At the same time, there will be a maximum cone angle of 0.51° suspended by the incoming solar radiation (S P Sukhatme and Nayak 2017). Though the conical angle is smaller, it acts upon the size of the concentrated solar fringe size. In Figure 3, the incident rays from the sun on the endpoints of the facets were shown. The incident rays are marked with red and violet colour. As the red-coloured incident rays reflect and make the boundary of the solar image, only those rays were considered in the determination of the solar image diameter.

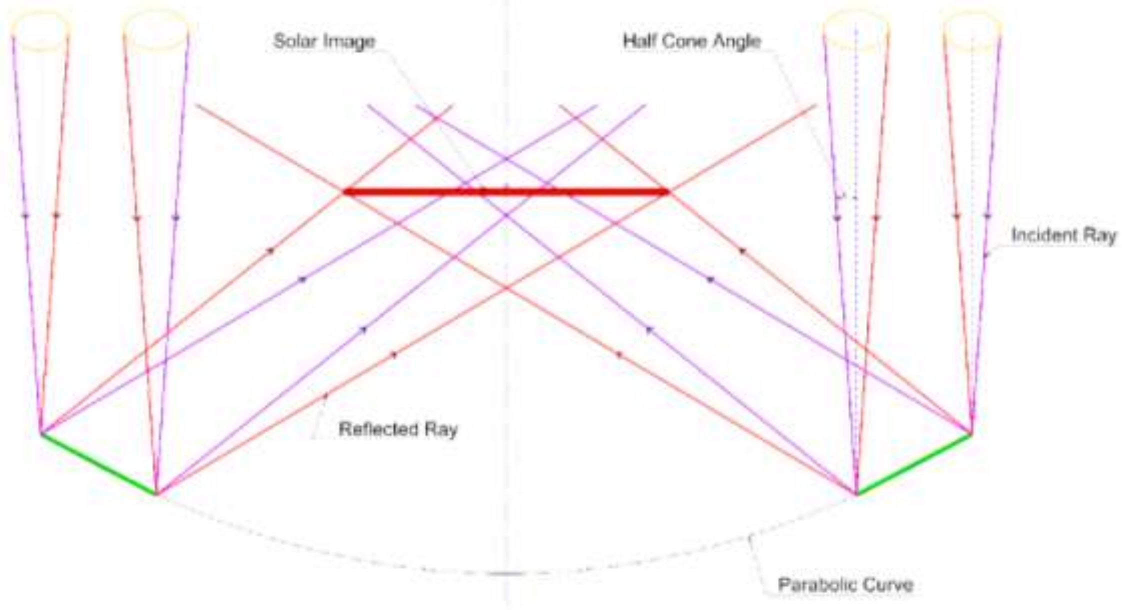

Figure 3: Solar Image formation of a parabolic dish concentrator by considering the solar conical angle.

The construction of the parabolic dish with flat facets on the utmost ends of the parabola was done by considering the incident rays which generate the boundary of the solar image. The reflected geometry is produced and presented in Figure 4 as per Snell's law of reflection.

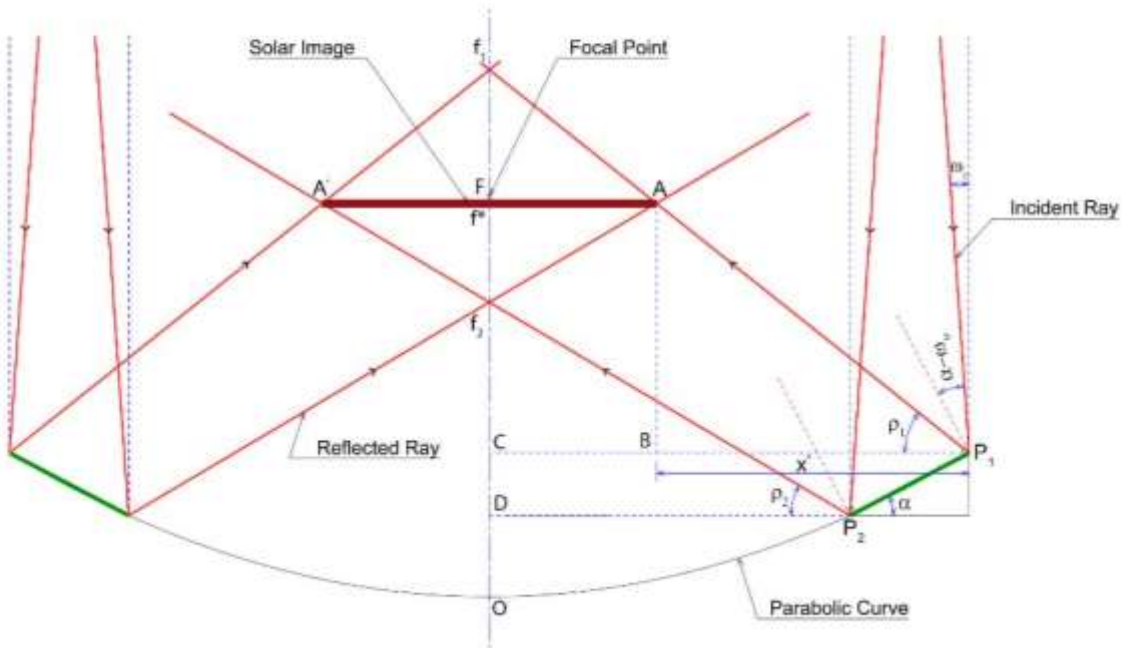

Figure 4: Solar Image based on extreme reflected rays.

From Figure 4, based on trigonometric law, the expression for x'' can be given as below.

$$x'' = \frac{f^{*} - y_1}{\tan(90 - (2\alpha - \omega_o))} \quad (7)$$

Hence, by using the following expression (8), the solar image diameter of a solar parabolic dish concentrator with a square flat facet can be determined.

$$d = D - 2x'' \tag{8}$$

2.4 Actual Solar Image location from the vertex (f*)

A shift in the solar image from the focal plane was noticed on the establishment of solar conical angle to the incident solar radiation and flat facets. Nevertheless, one of the points among the intersection of extreme reflected rays is on the axis. Hence, for determining the distance of the actual solar image from the vertex, in the beginning, the point of intersection (f_1 & f_2) of the extreme reflected rays must be determined. Once the points f_1 and f_2 were determined by applying the mathematical theorem, the exact shift can be predicted. The expression for finding the exact shift of the solar image is given as follows.

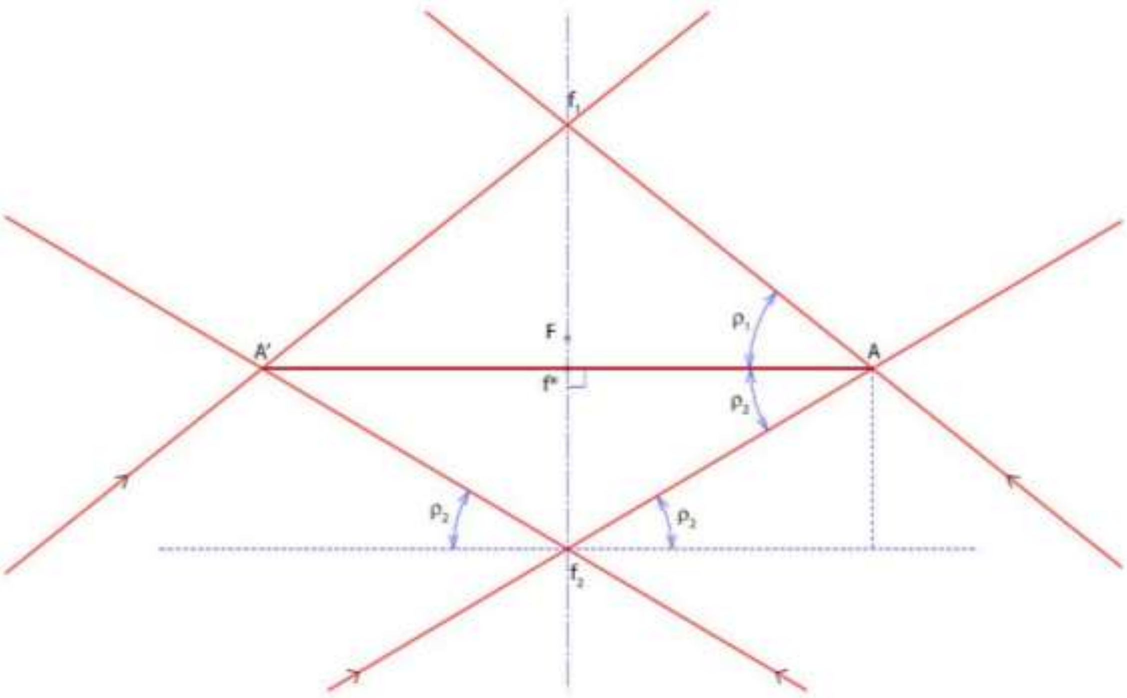

Figure 5: Focal region of the parabolic dish with facet considering the conical angle.

Considering the solar image region as shown in Figure 5, the exact shift of the solar image and the solar image distance from the apex point of the parabola along its axis can be determined by using the following expression (9).

$$f^* = \frac{f_1 + Gf_2}{1+G} \tag{9}$$

where, $G = \frac{\tan \rho_1}{\tan \rho_2}$, $\rho_1 = 90 - (2\alpha - \omega_o)$, $\rho_2 = 90 - (2\alpha + \omega_o)$

2.5 Determination of Surface Slope Error due to facets (f*)

For an ideal parabola, all the incident rays parallel to the axis will converge at the focal point of the parabola. A surface slope error is determined as the angular difference between the actual surface normal and the ideal surface normal of the parabolic surface (Stynes and Ihas 2012). When facets are introduced over the parabolic surface, the alignments of facets impart the surface slope error to the parabolic profile. Applying the following expression, the maximum surface slope error due to facets can be determined (expression 10).

$$\theta_r = \frac{\phi}{2} - \alpha \quad (10)$$

2.6 Solar Image Calculator

Established on the analytical model developed, a portable computer application "Solar Image Calculator" was developed using Python programming language. This lets the users calculate the actual solar image size and the solar image location along the parabolic axis. Rim diameter (D), focal length (f), rim angle (ϕ), length of the facet (L) was taken as the input parameters for the dish concentrator and also the half conical angle (ω_o) was given as solar radiation parameter. Any three parameters out of the dish parameters are required to compute the solar image.

2.7 The existing method for determining the solar image

The property of parabola is to converge all the rays which are coming parallel to the axis at the focal point. Consequently, hypothetically for an ideal parabola, every single parallel ray concentrates at the focal point. But on account of solar optics, there exists a most conical disc angle of 0.51° because of the bigger sun diameter. On account of this, a little greater solar image will be acquired rather than a point. The formation of the solar image for an ideal parabolic dish concentrator over the focal plane is demonstrated in Figure 6. The reflections at extreme points of the parabolic profile, structure the boundary of the solar image, the outermost reflections are as shown in Figure 6. The existing geometrical optic relations for finding the optimum solar image diameter are expressed by Kaushika which are given below in equations 11 and 12 (Kaushika 1993).

The solar image diameter for an ideal paraboloidal dish concentrator:

$$d = \frac{4 \times f(\tan \omega_0)}{(1+\cos\varphi)(\cos\varphi)} \quad (11)$$

for the paraboloidal dish concentrator with facets:

$$d = \frac{4 \times f(\tan(\omega_0 + \Delta\omega_0))}{(1+\cos\varphi)(\cos\varphi)} \quad (12)$$

Where, $\Delta\omega_o = \frac{L(1+\cos\phi)\times 180}{4\pi f}$ is a correction factor based on the facet size, focal length, and rim angle.

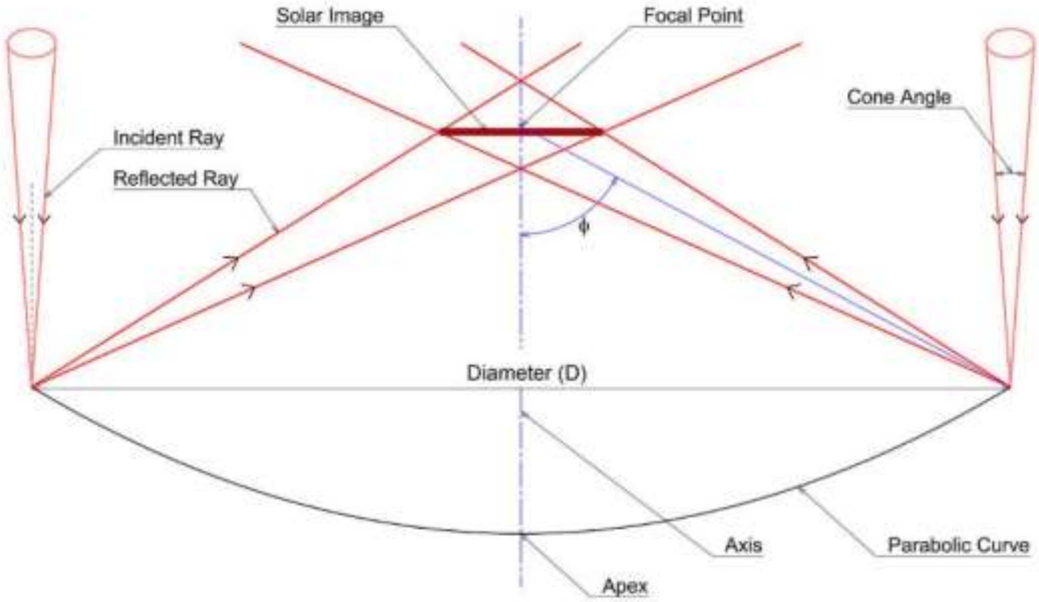

Figure 6: Solar Image formation of an ideal parabolic dish concentrator.

2.7.1 Study of existing analytical model:

To determine the precision and reliability of the existing analytical relationship, it was compared to the graphical model for various combinations of parabolic dish parameters (dish diameter, rim angle, and facet length). Three different ranges for parabola geometrical parameters and facet sizes are recorded in Table 1 (from minimum to maximum values) are used to conduct the numerical experiments.

Table 1: Dataset for parabolic dish parameters and facet sizes

	Diameter (mm)	Rim Angle (deg.)	Length of facet (mm)
Min	1000	40	40
Max	10000	85	240
Step size	500	5	10

2.8 Validation:

The current analytical model has been validated with the available experimental data (Sahu et al. 2020, 2021) in this section. A solar parabolic dish concentrator of 12.5 m^2 aperture area with square mirror of 0.075 m side as reflector has been considered for validation of the proposed model. The actual focal image obtained from the experiment was 0.147 m, whereas the value obtained from the present model is 0.134 m. Therefore, the current model is in good agreement with deviation of 8.84% with the experimental value. Table 2 shows the specification of the parabolic concentrator used in the experimental work (Sahu et al. 2020, 2021). Figure 7 shows the parabolic dish concentrator used for experimental work.

Table 2: Specifications of dish concentrator (Sahu et al. 2021)

Parameters	Value
Dish Diameter	4 m
Aperture area of dish	12.6 m^2
Rim Angle	45°
F/D ratio	0.6
Facet Shape	Square
Facet Size	0.075 m × 0.075 m
Focal image diameter	0.147 m

Figure 7: Parabolic dish concentrator with square facets(Sahu et al. 2021)

3 Result and Discussion

Although solar radiations are thought to be parallel beams, their conical angle has a significant impact on the solar image dimension and concentration ratio. The impact of the conical angle, rim angle, facet length, and diameter on parabolic dish characteristics is shown and discussed in this section.

3.1 Influence of Conical Angle:

In the initial step, solar radiation emanating from the sun is considered as parallel rays (without considering the solar cone angle), where the direction of rays is believed to be parallel to the axis of the parabolic profile. Graphical images have been generated for all the 3990 sets and measured the focal lengths, solar image diameters, and distances of the solar image from the apex automatically employing computer-aided design (CAD) programming.

Based on the observations, the influence of conical angle on solar image dimension is depicted in Figure 8. By maintaining the facet size constant, the graphical picture depicts the variation of solar image diameter concerning Rim Angle. Only the dish diameters of 1 m, 5 m, and 10 m are used to improve interpretation clarity. As the rim angle increases, the diameter of the solar image expands exponentially. As the diameter of the dish rises, the conical angle has a considerable impact on the solar image diameter. When comparing parallel rays without considering conical angle, it should be noted that the variance in solar image diameter is not as dramatic even with a change in diameter.

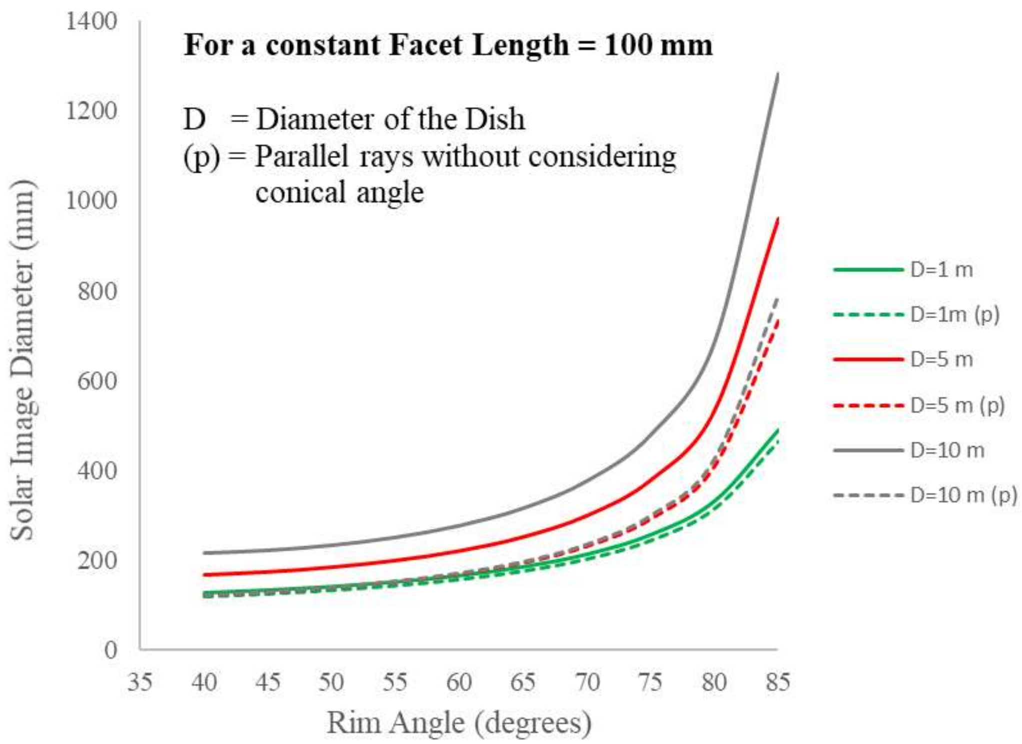

Figure 8: Influence of Conical Angle on Solar Image Diameter concerning Rim Angle

Because the conical angle affects the solar image, the concentration ratio will be changed as well. Figure 9 shows the effect of conical angle on geometrical concentration ratio as a function of rim angle change. The conical angle has a substantial influence on the concentration ratio, as can be seen in the graph. The conical angle influence is less significant for low dish diameters and larger rim angles, according to the results.

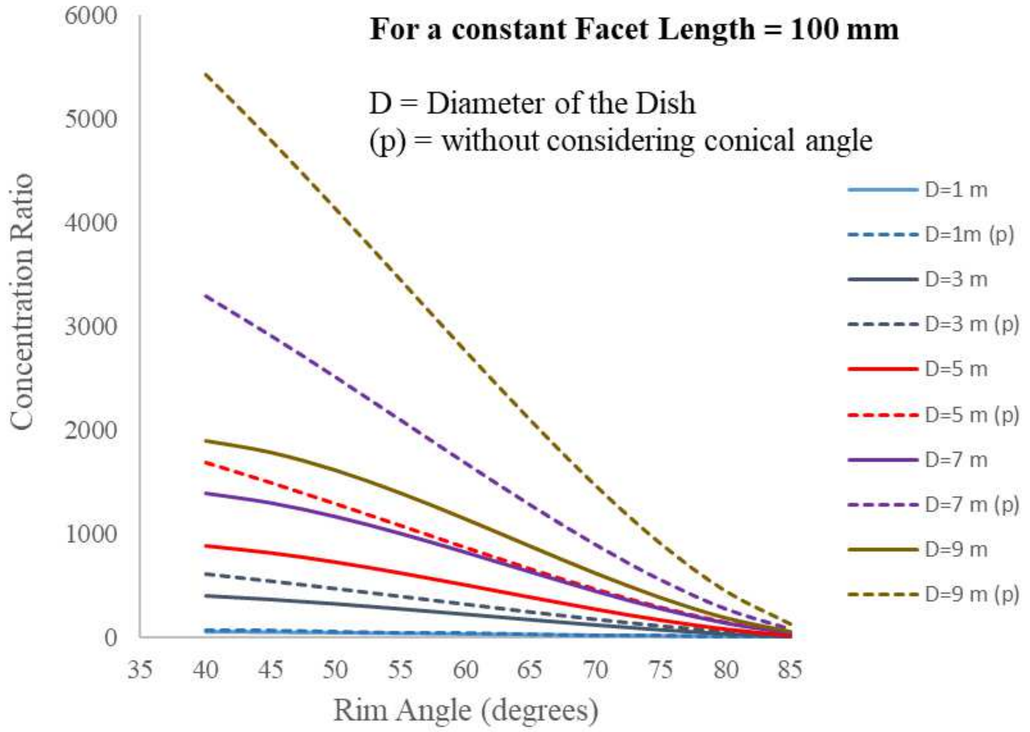

Figure 9: Influence of Conical Angle on Concentration Ratio concerning Rim Angle

3.2 Prediction of Solar Image Diameter:

The computed and attained solar image diameter are plotted amongst the different design parameters to review the behaviour of the solar image diameter.

Figure 10 illustrates the graph between the rim angle (ϕ) and the solar image diameter (d), retaining a constant facet size of 100 mm and dish diameter of six different values (D= 1 m, 2 m, 4 m, 6 m, 8 m, 10 m). It is observed from the illustration that as the rim angle grows the solar image diameter also increases. However, the value of the solar image lies below 500 mm up to 75° rim angle, after that the solar image size increases steeply to the maximum of 1280 mm. Hence, based on this graph it is suggested to choose the parabolic dish concentrator of rim angle less than 75° to get fair performance.

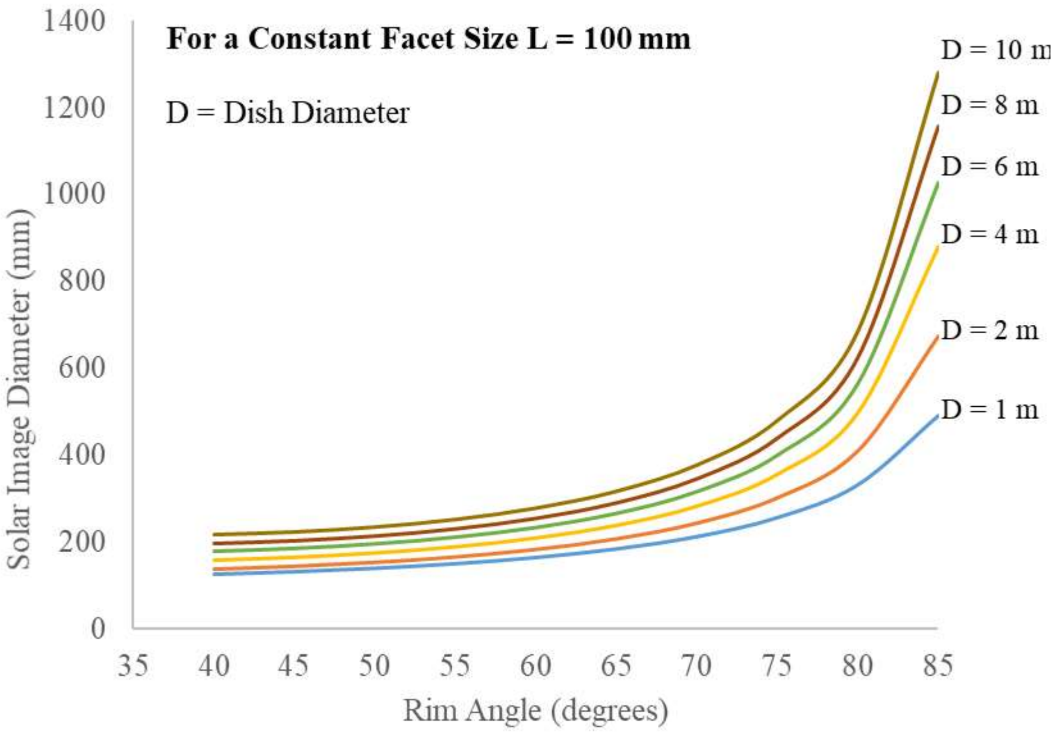

Figure 10: Variation of Solar Image Diameter (d) for Rim angle(ϕ).

The concentration ratio is one of the crucial factors which decides the performance of the solar parabolic dish concentrator system. The geometrical concentration ratio is the ratio of the projected area of the parabolic dish to the area of the receiver. Figure 11 indicates the variation of concentration ratio concerning the rim angle for the developed model for the range of dish diameter considered.

On analysing rim angle, the concentration ratio decreases as the rim angle increases. The concentration ratio was noted to be maximum for the lower rim angle in the observed range and showed a significant increase in concentration ratio.

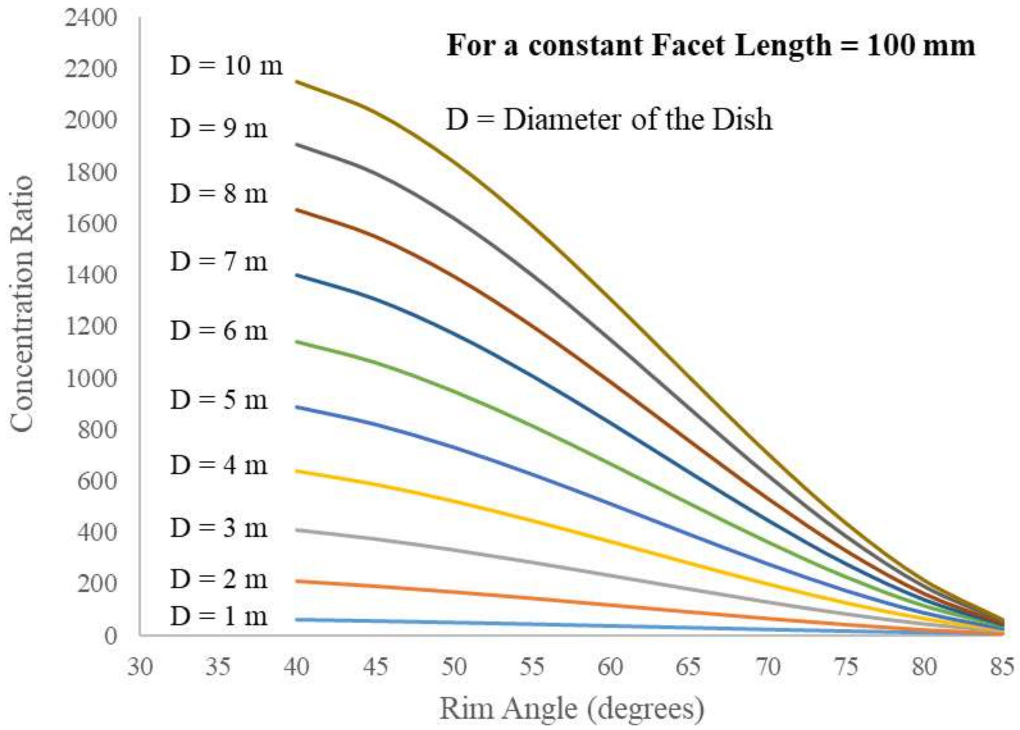

Figure 11: Influence of Rim Angle on Concentration Ratio

Figure 12 illustrates the graph between the dish diameter and the solar image diameter for a constant facet size of 100 mm and rim angle of eight different values (ϕ = 40°, 55°, 60°, 65°, 70°, 80°, 85°). It reveals that the solar image diameter keeps increasing as the diameter increases irrespective of the facet length and rim angle. However, the trend follows to be linearly increasing up to the rim angle of 75°, above that the variation of solar image diameter is more significant and not linear.

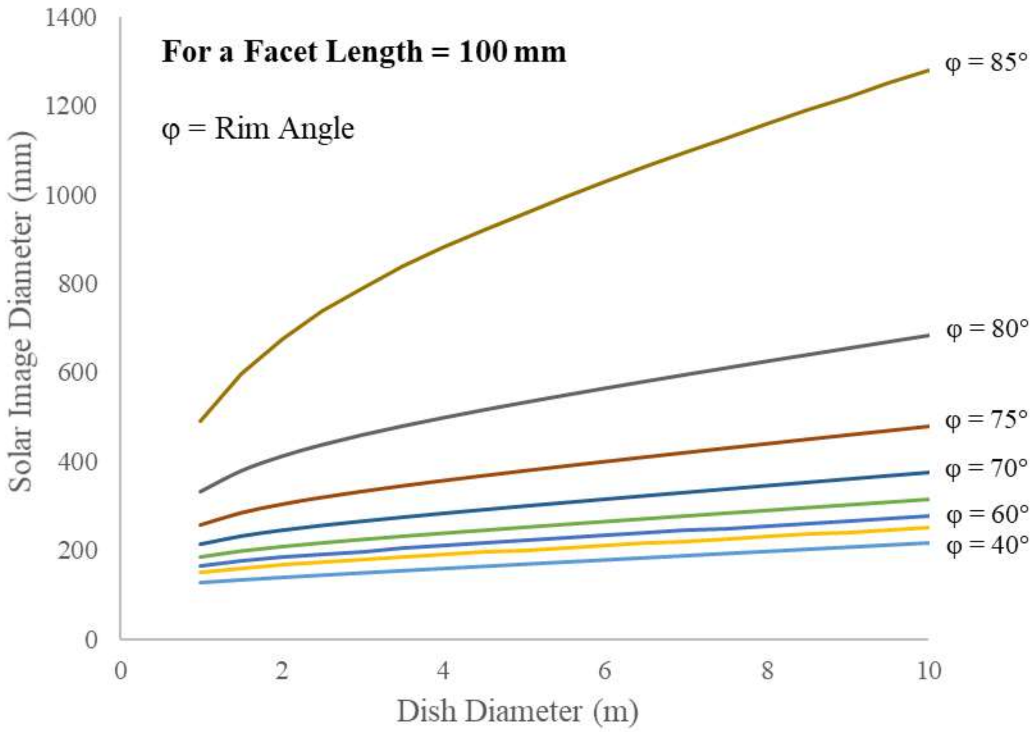

Figure 12: Variation of Solar Image Diameter (d) for Dish Diameter (D).

Figure 13 reveals the variation of solar image diameter in connection with the change in facet size at a constant rim angle of 45° for ten different values of dish diameter (1 m to 10 m). From the graphical illustration, it is found that the solar image size varies linearly as the facet size increases. However, a small deviation from linearity is observed at the lower dish diameters.

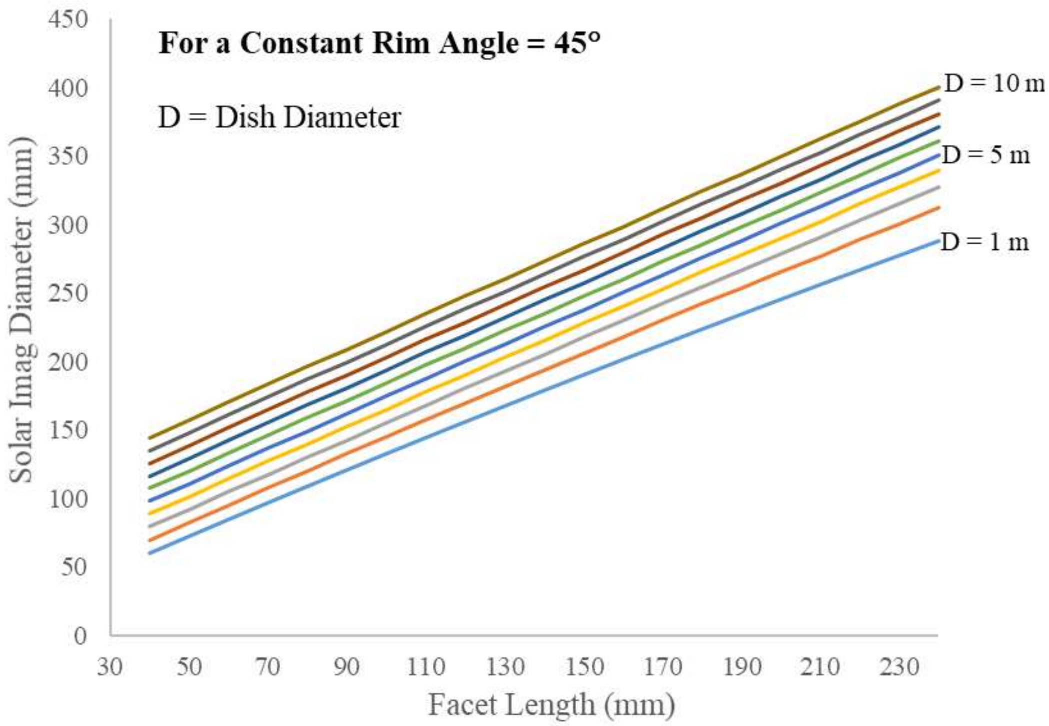

Figure 13: Variation of Solar Image Diameter (d) for the facet size (L).

Figure 14 illustrates the graph between the concentration ratio and the facet length for a constant dish diameter of 5 m and rim angle of ten different values from 40° to 85° with an increment of 5°. Based on the graph, it is observed that the concentration ratio exponentially decreases as the facet size increases. However, the concentration ratio steeply decreases for greater diameter dishes than the lesser ones. According to the result analyzed it is suggested to go for fewer size facets for attaining a higher concentration ratio.

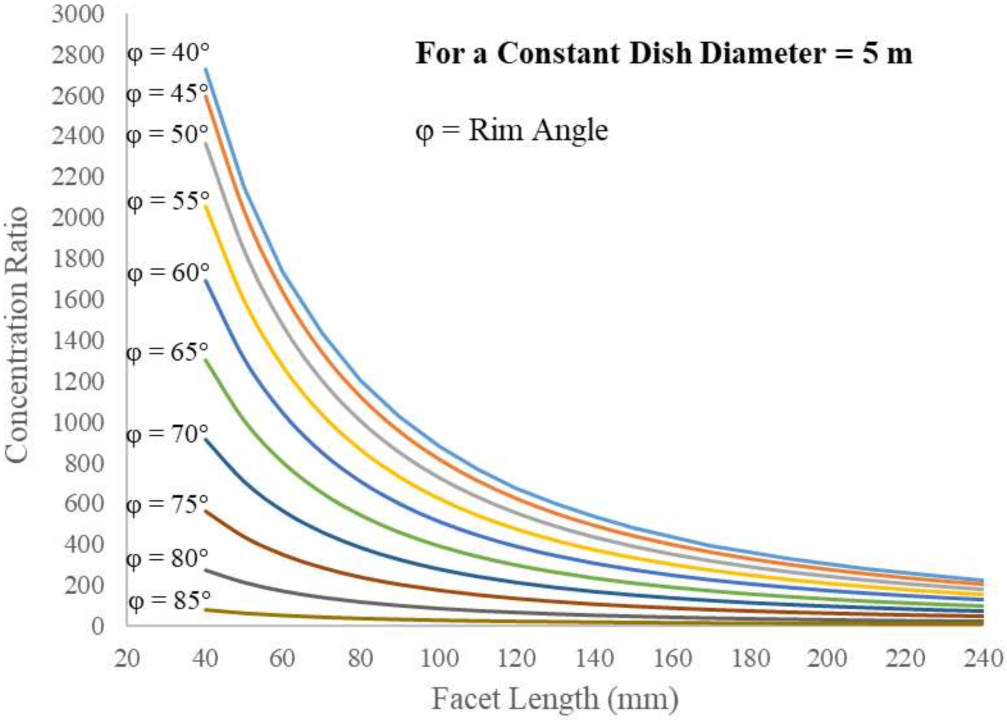

Figure 14: Influence of Facet Size on Concentration Ratio

3.3 Influence of Facet Size on Surface Slope Error:

Figure 15 shows the variation of the surface slope error on a parabolic dish concentrator with a rim angle of 45° due to the discretized mirror facets over the surface. From the graph, it is observed that the surface slope error, varies linearly as the facet size is varied. Also, the use of flat facets as an alternative to double curved facet for concentrator affects the surface with lower slope error for lesser diameter one than the larger diameter dish. Hence, as per the graph, it can be suggested that the dish diameters of sizes lesser than 5m have minimum surface slope error compared to higher diameter for the same facet size.

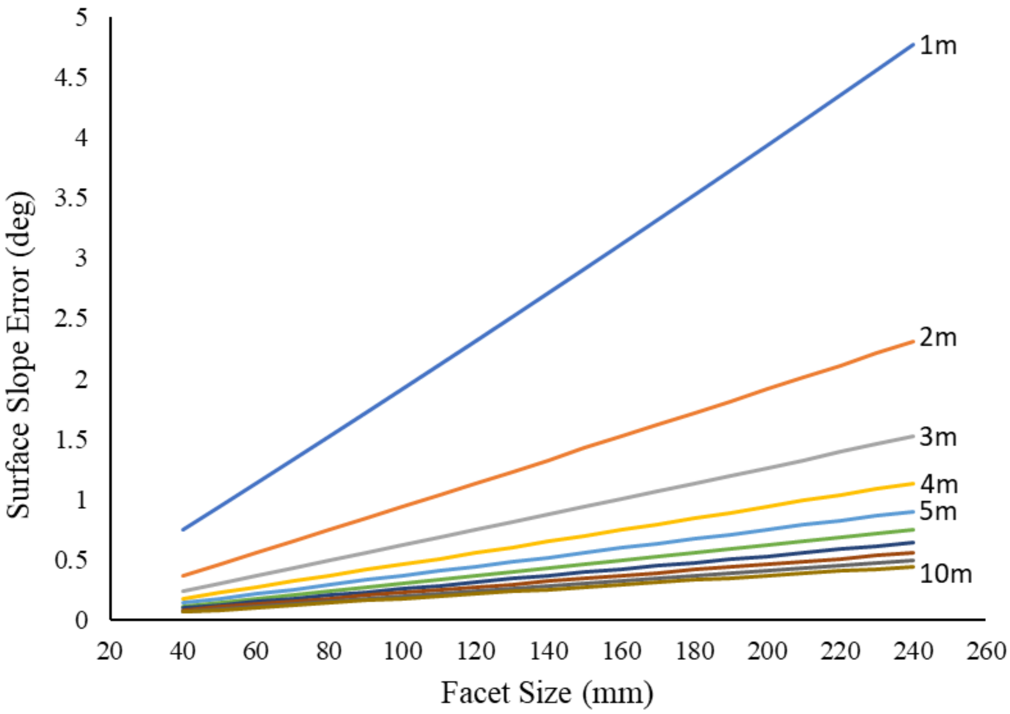

Figure 15: Influence of Facet Size on Surface Slope Error.

4 Conclusions

Among the point focussing type solar concentrators, the solar parabolic dish got featured because of its superior concentration ratio, better heat flux over the receiver, modular arrangement, and advanced thermal efficiency. The main results of this study can be summarized as below:

- The proposed technique gives the actual solar image diameter as well as tends to how much drift in the solar image along the axis from the focal plane.
- Although there is a shift in the actual solar image location the deviation is not so huge. Be that as it may, during the development of larger dishes, the shift ought to be considered for ideal outcomes.
- By utilizing the proposed model, the specific actual solar image size and area of a solar parabolic dish concentrator with square facets can be resolved.
- This amplifies the area at which solar radiation incident over the parabolic reflector, as the area blocked by the receiver decreases.
- The decrease of the solar image distance across prompts a lessening in heat loss from the receiver because of convective and radiative heat transfer, as the receiver surface area shrinks.

- Likewise, it prompts an expansion in both the geometrical and optical concentration ratio of the parabolic dish concentrator. By acquiring the actual solar image, a high temperature can be gotten on the receiver.
- As an extra factor, in view of the reflection point (ρ1) of the extraordinary radiation, the secondary reflectors or cavity receiver profile can be streamlined.
- The characteristic study of surface slope error due to the introduction of flat mirror facet will help the researchers to choose the dish and facet size according to their requirements.
- Consequently, the present descriptive model is in good agreement with the experimental value. As a result, it can be utilized to predict the focal image diameter and its area for the fixed parabolic dish parameters and facet size theoretically.

Declarations

Ethics approval and consent to participate*:* Not applicable

Consent for Publication: Not applicable

Availability of data and materials: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request

Competing interests: The authors declare that they have no competing interests.

Funding: Not applicable

Author Contributions - CRediT author statement

Arjun Singh Kopalakrishnaswami: Conceptualization, Formal analysis, Investigation, Data Curation, Writing - Original Draft.

Reyhaneh Loni: Conceptualization, Formal analysis, Investigation, Data Curation, Writing - Original Draft.

Gholamhassan Najafi: Conceptualization, Validation, Resources, Writing - Review & Editing, Supervision,

Sendhil Kumar Natarajan*:* Conceptualization, Validation, Resources, Writing - Review & Editing, Supervision, Project administration.

Acknowledgments

The authors would like to express their gratitude to the National Institute of Technology Puducherry, Karaikal, and Tarbiat Modares University for their support and research facilities.

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