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CHARACTERIZATION OF PARABOLIC CONCENTRATOR DISH WITH FLAT MIRRORS

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Abstract. *Environmental policies regulating fossil fuel consumption have become increasingly stringent. Consequently, the electric power generation matrix is now compelled to explore strategies that enhance the involvement of renewable sources, particularly solar power. However, the utilization of parabolic dish technology for heat and electricity production has been largely unexplored in Brazil, despite the country's high solar irradiation rates throughout the year. Hence, this study proposes a design strategy for a solar concentrator dish that employs flat mirrors as a replacement for a single parabolic mirror. The flat mirrors with trapezoidal facets are compared using a Monte Carlo simulation conducted with the Tonatiuh program. Through this approach, geometric characteristics, reflective material properties, and the optimal number of subdivisions required to closely approximate a commercial parabolic mirror are optimized. Ultimately, the computational simulation facilitates the evaluation of photon distribution in the receiver and the amount of concentrated heat power in the cylindrical and circular areas. These findings demonstrate the feasibility of substituting the parabolic mirror with one constructed using flat facets.*

Keywords: Solar energy, Solar concentration, Monte Carlo Simulation, Parabolic dish, Brazil.

1. INTRODUCTION

To mitigate the problems caused using non-renewable sources, the exploitation of clean energy sources becomes necessary. Therefore, research has been reported on how to efficiently utilize renewable energy resources. One of the most significant resources is solar energy, which has been utilized for water heating, direct electricity generation through photovoltaic energy, and steam generation through parabolic solar collectors. It is estimated that the Earth receives an approximate solar irradiance power of 1,000 W/m² in a day (Winston et al., 2020). Esch (2010) and Liu et al. (2009) demonstrated that this amount of irradiance could generate around 8,500 TW worldwide and concluded that solar energy alone has the capacity to meet the current energy demand.

Currently, there are projects related to the implementation of solar concentrators carried out by research centers, universities, and companies to design and analyze the reliability and performance of solar concentrators. Within their studies, it is detailed that parabolic dish solar concentrators have the highest efficiency in converting solar energy into electricity, achieving an efficiency of 29.4% (Droher and Squier, 1986). Such systems possess high optical efficiency and low losses for thermal engine ignition, making parabolic dishes one of the most accessible infrastructures for solar energy transformation. Additionally, these systems are typically used to design small to moderate capacity applications, typically in the range of ten kilowatts, which are suitable for remote energy needs in rural areas and locations far from the national electric grid. In the case of requiring a higher capacity installation, the interconnection of small solar dish power plants is implemented (Lovegrove et al., 2011).

Parabolic concentrator dishes offer high thermal and optical efficiency but have a high construction cost per unit area. Most studies conducted thus far have focused on the thermal analysis of the solar energy conversion process, including the engine, rather than the design methodology itself. Therefore, this study presents a flat mirror concentrator dish that resembles the geometry of a parabolic concentrator, considering the following aspects: (a) designing the geometry of the flat mirror concentrator dish to capture direct radiation; (b) parameterizing the flat mirrors in the Tonatiuh program based on reflectance indices, material type, number of flat mirrors, and number of rings through simulations that evaluate solar radiation; (c) characterizing the behavior of the solar technology through graphs to determine the optimal number of flat mirrors for sizing the concentrator.

2. LITERATURE REVIEW

2.1 Solar energy and thecnology

Brazil has privileged climatic conditions for the utilization of heliothermic energy, as there is a significant amount of direct irradiation in a large part of the country, particularly in areas with low humidity, as shown in Figure 1. Additionally, there is the availability of relatively low-cost land compared to other countries, which enhances the potential for installing parabolic solar concentrator (CSP) plants. Therefore, it is crucial for the country to master the chain of new technologies such as solar concentrators, which can be a valuable source for electricity generation or as a means of generating heat in the form of vapor, widely used in industrial processes (Sandoval et. al., 2019).
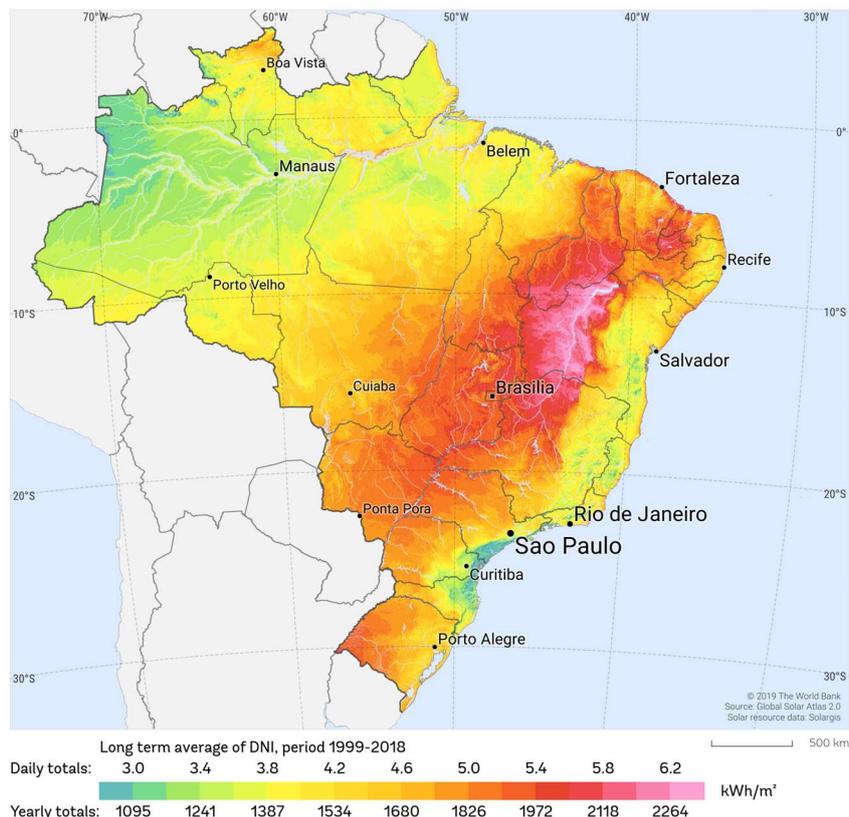
Figure 1. Map of direct normal irradiation (DNI) in Brazil. Source: https://globalsolaratlas.info/.

In heliothermal generation technology four basic systems are identified, the collection system or collector consisting of the concentrator and the receiver, the energy transport system, the storage system, and the power conversion system (Kalogirou, 2013). The concentrators are composed of flat or curved mirrors that track the movement of the sun through mechatronic mechanisms designed for solar tracking. They are direct solar radiation to a receiver, where the conversion of solar energy into thermal energy takes place. A heat transfer fluid passes through this receiver, responsible for exchanging heat with the receiver and supplying it to the hot part of a power cycle (Kalogirou, 2013).

The parabolic dish technology is characterized by a point focus and a movable receiver, meaning that the receiver tracks the sun along with the collector in two axes and is thus capable of pointing directly at the sun from sunrise to sunset (Sandoval et al., 2019). The parabolic dish concentrator is an autonomous power generation unit that can operate independently, suitable for use in remote areas away from major urban centers or as part of a plant composed of multiple dishes. As illustrated in Figure 2, it consists of the collector, which is an assembly of disk-shaped mirrors typically ranging from 5 m to 15 m in diameter, a receiver, and a Stirling engine or a microturbine, which is connected to an alternator (Kalogirou, 2013).

The construction of a flat mirror concentrator dish is based on the basic components of a parabolic solar concentrator dish, including a solar receiver, the dish mirror (reflector), the solar tracking system, and the base support structure as illustrated in Figure 2b.
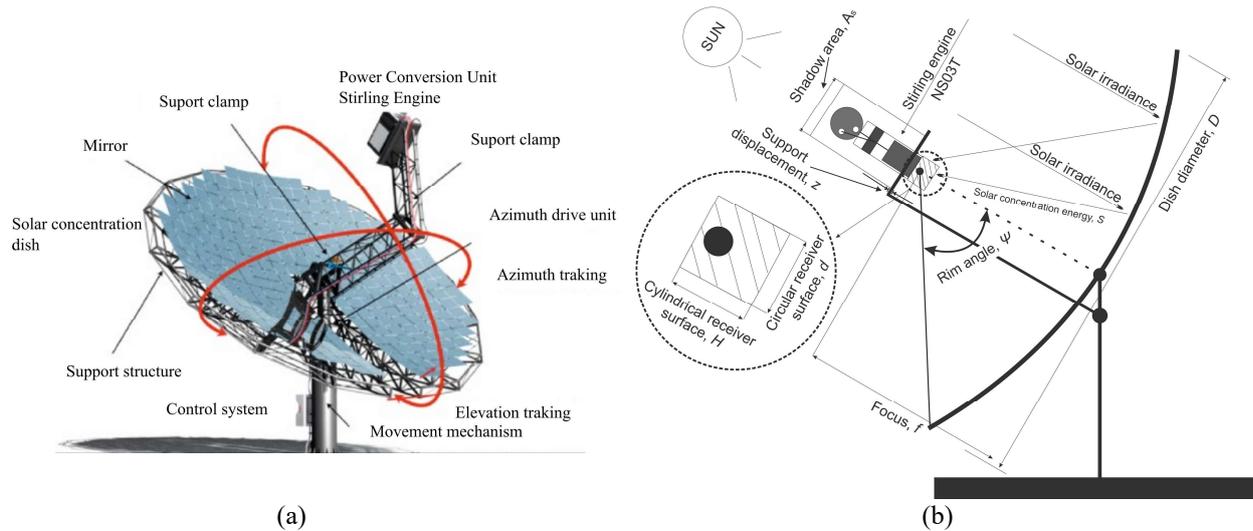
Figure 2. (a) Parabolic concentrator dish with Stirling engine as PCU. Source: www.concentrating.cz/technology (modified). (b) Dish/Stirling system - geometric parameters. Source: Sandoval et. al (2019).

In the receiver, solar energy concentrated by the mirrors is converted into thermal energy by heating the circulating fluid, usually air, although hydrogen or helium can also be used (Baharoon et al., 2015). This heated fluid drives the Stirling engine, which converts thermal energy into mechanical energy. By coupling an electric generator, the mechanical energy is further transformed into electrical energy (Sandoval et al., 2019).

The reflector geometry is a profile formed by the various connected flat mirrors. For the flat mirrors, the angle of incidence is equal to the angle of reflection with respect to an imaginary line perpendicular to each mirror. This phenomenon can be observed in Figure 3.
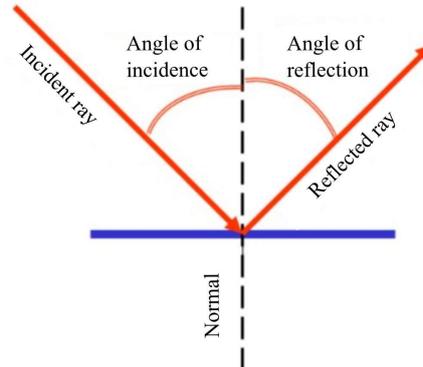

Figure 3. Reflection in a flat mirror.

Several materials are used for the mirrored surface, such as reflective mirror, polished reflective steel, reflective aluminum foil, among others. The best material is determined by its ability to reflect solar irradiance onto the dish. Likewise, according to Sutter et al. (2018), the most used materials for this purpose are polished aluminum foil, glass mirror, and reflective silver polymer.

3. MATERIALS AND METHODS

The geometric construction is expressed based on direct reflection described in the literature review. To do so, it is necessary to parameterize the measurements according to which the study will be initiated. In this study, the following data will be used: i) Focus distance: 2 m, ii) receptor diameter: 1 m, iii) number of mirrors for the study: seven units.

A profile is developed where multiple flat mirrors are connected based on the angle of incidence described in the literature review. In other words, the angle equals the angle of reflection with respect to an imaginary line perpendicular to each mirror as observed in Figure 3. In this study, the design begins to take shape in the academic version of SolidWorks software, with the dimensions delimited and fully defined. Each line is extruded onto its respective plane, resulting in a profile of seven consecutive flat mirrors with a study thickness of 0.003 m, resembling the profile of a parabolic concentrator, as shown in Figure 4a and 4b.
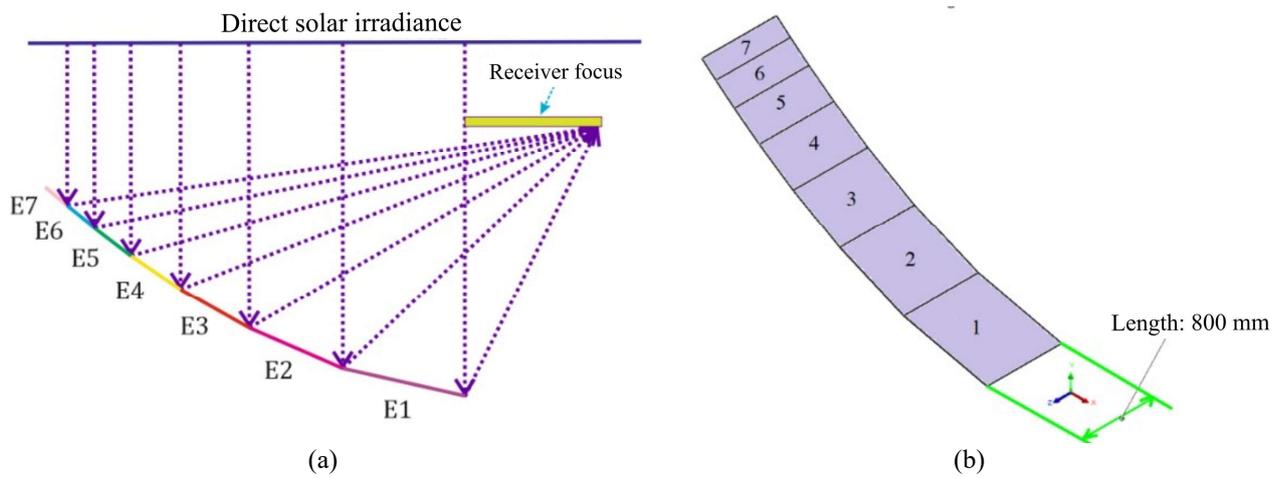
Figure 4. a) Development of the 7-flat-mirror dish. b) solid shape.

A circular matrix with 28 repetitions is introduced around the y-axis. This value was chosen, leaving a gap between each set of mirrors as a necessary measure for assembly in a future installation. The result can be observed in Figure 5, where the intersections of the rectangular profiles have now become trapezoidal sections.
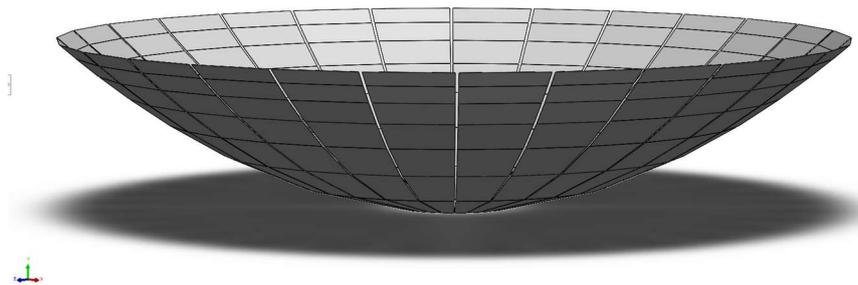

Figure 5. Solar concentrator dish with flat mirrors model

After designing the parabolic dish, it is proceeded to import the solid into the Tonatiuh environment where parameters for analysis are established, such as irradiance, thetaMax, sun position, m_reflectivity, sigma Slope, among others presented in Table 1.

The value of irradiance, equal to 1,000 W/m², is used within the definition of solar light. The value of "thetaMax" is set to the standard value of 0.00465. The reflective material is an anti-soiling coated glass with a reflectance of 0.945. The grid divisions are configured as 50x50, and ray tracing is set to 75,000,000.

Table 1. Parameters for the analysis of the parabolic dish in the Tonatiuh environment.

Parameter	Value
m_reflectivity	0,945
m_sigmaSlope	4,469
m_distribution	Normal

4. RESULTS

To analyze the contribution of each ring of the dish, the solid is subdivided into rings with flat mirrors of the same dimensions. These subdivisions are shown in Figure 6a, and a simulation example on Tonatiuh is presented in Figure 6b.
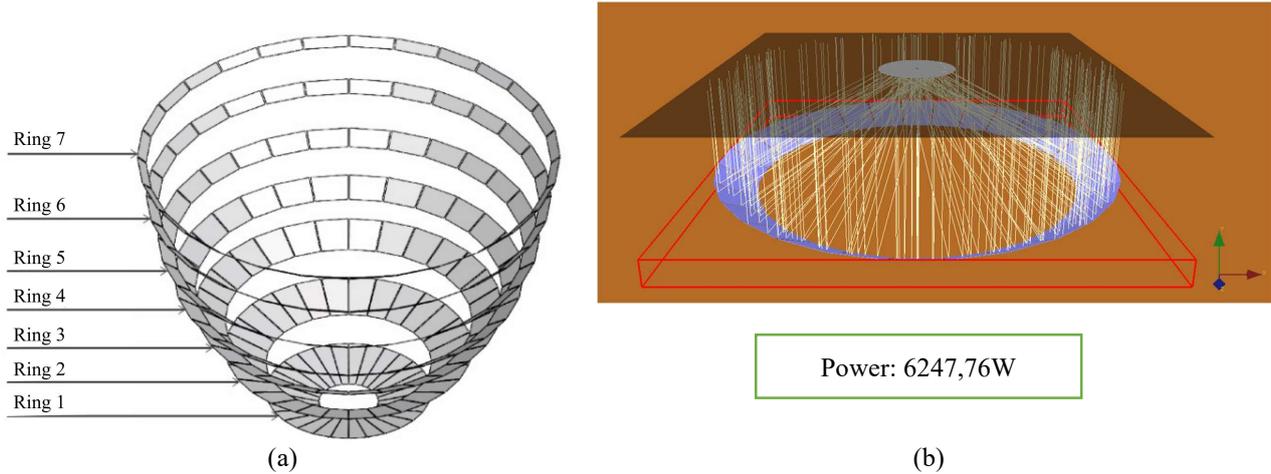
Power: 6247,76W

(a)   (b)

Figure 6. Solar concentrator dish with flat mirrors.

After conducting the tests, Table 2 shows the power supplied by each ring in relation to that of the collector dish. From the initial ring, there is a noticeable progressive increase in power, with a 14.7% rise to a peak value of 20.4% in the second ring. However, beyond this point, the supplied power starts to decline, reaching a minimum of 2.4% compared to the power provided by the seventh ring. As illustrated in Figure 7, the critical values depicted in the graph are those that fall below the average energy contribution percentage, specifically rings 6 and 7. It is worth mentioning that ring 5 also falls below this threshold but exhibits a decreasing trend.

Table 2. Contribution power of each ring in relation to the total concentrator dish.

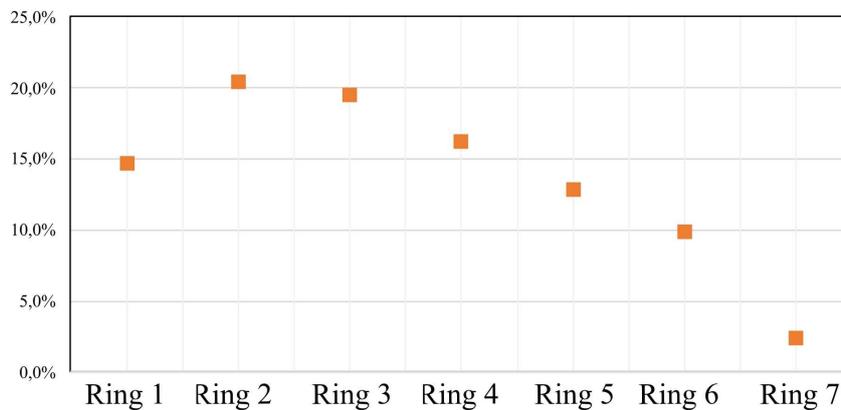| Ring	Power ring (W)	Relative power
1	4729	14.7%
2	6551	20.4%
3	6247	19.4%
4	5222	16.3%
5	4135	12.9%
6	3183	9.9%
7	784	2.4%
Dish	30854	

Figure 7. Power dispersion of the supplied data in relation to the total.

5. CONCLUSION

In conclusion, the presented design methodology successfully addresses the realization of a geometry with initial measurements and utilizes the Tonatiuh program for solar irradiance simulation. Through this approach, the influence of each studied component, organized in rings, has been determined.

The analysis revealed that among the seven proposed rings, the first four demonstrate optimal performance, while the contribution of the last three rings in terms of power output diminishes. These findings suggest that investing in the last ring would be unnecessary as it cannot effectively support the generated power relative to its collection area. Notably, the seventh ring contributes 2.44% to the power output of the disk but occupies 9.39% of the total area.

By employing a parabolic geometry resembling flat mirrors and utilizing the theory of direct radiation, the research has demonstrated the efficient capture of solar energy while minimizing energy loss at the receiver of the solar collector.

Significantly, the proposed configuration allows for an effective observation of material quantity, material type, and geometry of the disk, resulting in an ideal output power. This approach eliminates the need for an excessive number of rings that do not contribute to the power output of the disk relative to the area they occupy.

These findings highlight the importance of considering the specific design parameters and optimizing the arrangement of components in solar collector systems. Future experimental development of this project should prioritize the utilization of the four optimal rings to maximize power output and minimize unnecessary investments.

6. REFERENCES

Baharoon, D.A., Rahman, H.A., Omar, W.Z.W. and Fadhl, S.O., 2015. Historical development of concentrating solar power technologies to generate clean electricity efficiently–A review. *Renewable and Sustainable Energy Reviews*, *41*, pp.996-1027.

Droher, J.J. and Squier, S.E., 1986. *Performance of the Vanguard Solar Dish-Stirling Engine Module. Final report* (No. EPRI-AP-4608). Rockwell International Corp., Canoga Park, CA (USA). Energy Technology Engineering Center.

Esch, J., 2009. Prolog to: Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?. *Proceedings of the IEEE*, *98*(1), pp.39-41.

Liu, Q., Yu, G. and Liu, J.J., 2009. Solar radiation as large-scale resource for energy-short world. *Energy & environment*, *20*(3), pp.319-329.

Lovegrove, K., Burgess, G. and Pye, J., 2011. A new 500 m² paraboloidal dish solar concentrator. *Solar energy*, *85*(4), pp.620-626.

Kalogirou, S.A., 2013. *Solar energy engineering: processes and systems*. Academic press.

Sandoval, O.R., Caetano, B.C., Borges, M.U., García, J.J. and Valle, R.M., 2019. Modelling, simulation and thermal analysis of a solar dish/Stirling system: a case study in Natal, Brazil. *Energy Conversion and Management*, *181*, pp.189-201.

Sutter, F., Montecchi, M., von Dahlen, H., Fernández-García, A. and Röger, M., 2018. The effect of incidence angle on the reflectance of solar mirrors. *Solar Energy Materials and Solar Cells*, *176*, pp.119-133.

Winston, R., Jiang, L., & Oliker, V. 2020. *Nonimaging Optics: Solar and Illumination System Methods, Design, and Performance*. CRC Press.

7. RESPONSIBILITY NOTICE

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