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Optical Design of a Solar Parabolic Concentrating Collector Based on Trapezoidal Reflective Petals

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Abstract: In this paper, detailed optical of the solar parabolic dish concentrator is presented. The system has diameter D = 2,800 mm and focal length f = 1,400 mm. The efficient conversion of solar radiation in heat at these temperature levels requires a use of concentrating solar collectors. In this paper, detailed optical design of the solar parabolic dish concentrator is presented. The parabolic dish of the solar system consists from 12 curvilinear trapezoidal reflective petals. This paper presents optical simulations of the parabolic solar concentrator unit using the ray-tracing software TracePro. The total flux on receiver and the distribution of irradiance for absorbed flux on center and periphery receiver are given. The total flux at the focal region is 4,031.3 W. The goal of this paper is to present optical design of a low-tech solar concentrator, that can be used as a potentially low-cost tool for laboratory-scale research on the medium-temperature thermal processes, cooling, industrial processes, solar cooking and polygeneration systems, etc.

Key words: Solar parabolic dish concentrator, optical analysis, solar energy, solar radiation.

1. Introduction

The device which is used to transform solar energy to heat is referred to a solar collector. Solar thermal collectors have been widely used to concentrate solar radiation and convert it into medium-high temperature thermal processes. They can be designed as various devices including solar cooker [1], solar hydrogen production [2, 3] and Dish Stirling system of harvest electricity [4, 5]. The main types of concentrating collectors are: parabolic dish, parabolic trough, power tower, and Fresnel collector with mirror or lens and stationary concentrating collectors. The ideal optical configuration for the solar parabolic thermal concentrator is a parabolic mirror. The parabolic mirror is very expensive to fabricate and it is cost escalating rapidly with increase of aperture area. The parabolic mirror can be designed with large number of elementary components known as reflecting petals or facets. Usually reflecting petals are made from glass and their thickness is from 0.7 mm to 1.0 mm. Traditionally, the optical analysis of radiation concentrators has been carried out by means of computer ray-trace programs. Recently, an interesting analytical solution for the optical performance of parabolic dish reflectors with flat receivers was presented by O'Neill and Hudson [6].

Their method for calculating the optical performance is fast and accurate but assumes that the radiation source is a uniform disk. Imhamed, et al. [7] have presented study that aims to develop a 3-D static solar concentrator that can be used as low cost and low energy substitute. Their goals were to design solar concentrator for production of portable hot water in rural India. They used ray tracing software for evaluation of the optical performance of a static 3-D EHC (elliptical hyperboloid concentrator). Optimization of the concentrator profile and geometry

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is carried out to improve the overall performance of system. Kashika and Reddy [8] used satellite dish of 2.405 m in diameter with aluminium frame as a reflector to reduce the weight of the structure and cost of the solar system. In their solar system, the average temperature of water vapor was 300 °C, when the absorber was placed at the focal point. Cost of their system was US$ 950. Ouederni, et al. [9] was testing parabolic concentrator of 2.2 m in diameter with reflecting coefficient 0.85. Average temperature in their system was 380 °C. Rafeeu and AbKadir [10] have presented simple exercise in designing, building and testing small laboratory scale parabolic concentrators. They made two dishes from acrylonitrile butadiene styrene and one from stainless steel. Three experimental models with various geometrical sizes and diameters were used to analyze the effect of geometry on a solar irradiation. Zhiqiang, et al. [11] presented a procedure to design a facet concentrator for a laboratory-scale research on medium—temperature thermal processes. The facet concentrator approximates a parabolic surface with a number of flat square facets supported by a parabolic frame and having two edges perpendicular to the concentrator axis. A 164—facet concentrator will deliver up to 8.15 kW of radiative power over 15 cm radius disk located in the focal plane. Their system had average concentration ratio exceeding 100. Ahmed and Khan [12] presented two prototype parabolic dishes: the Shenandoah dish and the parabolic dish concentrator, in jet propulsion laboratory. The Shenandoah dish was designed to heat silicone oil in one pass to 400 °C. The Shenandoah dish is 7 m parabolic reflecting dish formed from 21 aluminum petals covered with special reflective layer on one side. The second parabolic dish (JPL parabolic dish concentrator) has parabolic reflector surface with 12 m diameter. Rebecca, et al. [13] investigated experimental evaluation of ammonia receiver geometries with a 9 m^2 dish concentrator. The 20 m^2 dish is mirrored with around 2,000 flat mirror tile facets arranged in concentric rings on a parabolic fiber glass support structure. Size of mirror facets is from 5 cm to 10 cm. Glen, et al. [14] analyzed optical performance of spherical reflecting elements for use with parabolic dish concentrators. This concentrator consists of 54 triangular mirrors. The effective rim angle for the dish is 46°. The 54 units are composed of nine separate panel shapes, each of shapes is duplicated six times. The focal length of system is 13.1 m. They compared the optical performances and manufacturing feasibility of collectors having such a combination of surfaces.

The decision to make solar parabolic concentrator with 12 petals is based on large number of design concepts that are realized in the world. This concept already proved useful in solar techniques, especially in production of heat and electrical energy as well as in trigeneration and polygeneration systems.

The basic idea behind this research is to start with primary concept of solar parabolic concentrator which will generate from 10 kW to 25 kW in polygeneration systems. Only with employment of parabolic concentrating systems, it is possible to obtain high temperatures in range from 200 °C to 800 °C and high thermal efficiency.

2. Optical Design of the Solar Parabolic Thermal Concentrator

The optical design of the solar parabolic thermal concentrator and operation are presented. Optical design is based on parabolic dish with 12 curvilinear trapezoidal petals. Solar dish concentrators are generally concentrators that concentrate solar energy in a small area known as focal point. Dimensions of reflecting surfaces in solar dish concentrator are determined by desired power at maximum levels of insolation and efficiency of collector conversion. Mathematical representation of parabolic concentrator is paraboloid which can be represented as a surface obtained by rotating parabola around axis which is shown in Fig. 1.

Mathematical equations for the parabolic dish solar

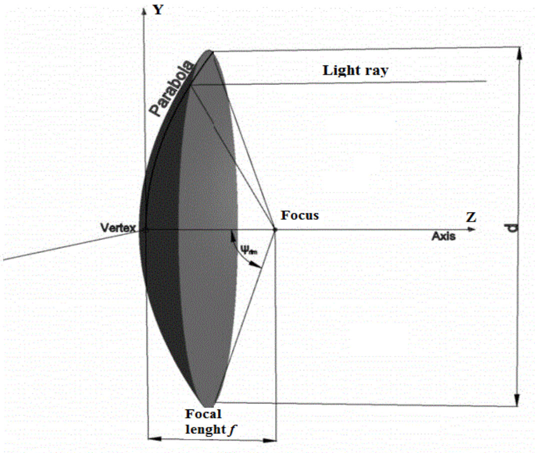


Fig. 1 Ideal shape of parabolic solar concentrator.

concentrator (Fig. 1) in Cartesian and cylindrical coordinate systems are defined as:

$$x^2 + y^2 = 4fz$$
$$z = r^2/4f \qquad (1)$$

where, x and y are coordinates in aperture plane; and z is distance from vertex measured along the line parallel with the paraboloid axis of symetry; f is focal length of paraboloid i.e., distance from the vertex to the focus along the aparboloid axis of symmetry. The relationship between the focal length and the diameter of parabolic dish is known as the relative aperture and it defines shape of the paraboloid and position of focal point. The shape of paraboloid can be also defined by rim angle ψ_{rim}. Usually paraboloids that are used in solar collectors have rim angles from 10° up to 90°. The relationship between the relative aperture and the rim angle is given by:

$$f/_D = \frac{1}{4\tan(\psi_{rim}{}^2)} \qquad (2)$$

The paraboloid with small rim angles have the focal point and receiver at large distance from the surface of concentrator. The paraboloid with rim angle smaller than 50° is used for cavity receivers while paraboloids with large rim angles are most appropriate for the external volumetric receivers (central receiver solar systems).

The geometric concentration ratio can be defined as the area of the collector aperture A_{app} divided by the surface area of the receiver A_{rec} and can be calculated by Eq. (3):

$$CR_g = \left(\sin^2\theta_a\right)^{-1} = A_c A_r{}^{-1} = A_{app} / A_{rec} \qquad (3)$$

The designed solar parabolic concentrator has geometric concentration ratio CR = 13,615.

Flux concentrating ratio can be defined as ratio of flux concentrated in a point I to incident solar flux $I_{b,\,n}$:

$$CR_{flux} = \frac{I}{I_{b,\ n}} \qquad (4)$$

2.1 Design Description of Solar Parabolic Concentrator

Mechanical design of the solar parabolic concentrator is done in 3D design software CATIA, Dassault systems, USA. Parabolic shape of solar concentrator is obtained by entering X and Y coordinates for selected points. For calculation of necessary points that define parabola public domain software Parabola Calculator 2.0 is used. The calculated coordinates (X and Y) for designed parabola are shown in Table 1.

Geometrical model of solar parabolic concentrator is parametrically designed from calculated coordinates and it is shown in Fig. 2. Selected model of solar dish concentrator with 12 petals requires very precise definition of parameters during geometrical modelling of system. Results obtained by optical analysis of solar concentration system are very much dependent on the selected method of the geometrical model generation.

A truncated paraboloid of revolution (circular paraboloid) is obtained by rotating the parabola segment about its axis (Fig. 3).

Consider a concentrator consisting of 12 trapezoidal reflective petals of identical non-overlapping trapezoidal segments. 3D model of trapezoidal reflective petal of solar parabolic concentrator is presented in Fig. 4.

Table 1 Coordinates of designed parabola.

X (cm)	-140.0	-116.6	-93.33	-70.00	-46.67	-23.33	0.0
Y (cm)	35	24.31	15.56	8.75	3.89	0.97	0.0
X (cm)	23.33	46.67	70.00	93.33	116.67	140	-
Y (cm)	0.97	3.83	8.75	15.56	24.31	35.00	-

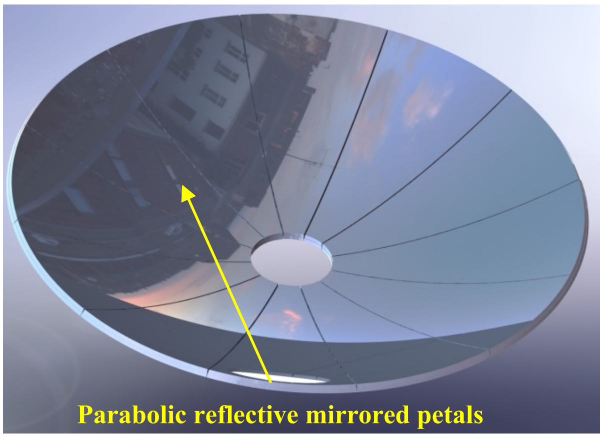


Fig. 2 Computer aided drafting model of solar parabolic dish concentrator.

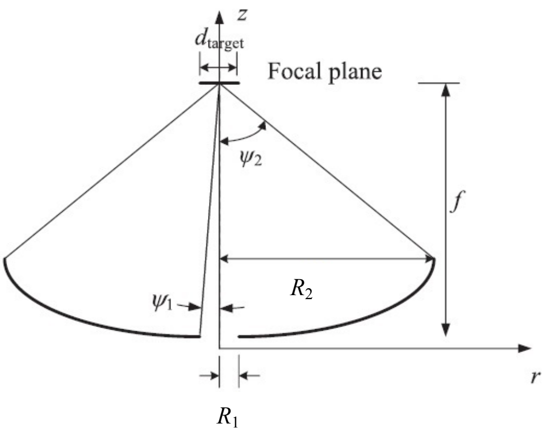


Fig. 3 Schematic of truncated parabola.

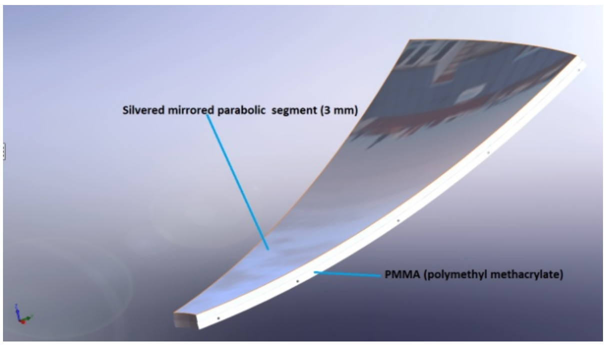


Fig. 4 Trapezoidal reflective petal of solar parabolic dish concentrator.

Detailed design parameters of solar parabolic concentrator are given in Table 2.

Receiver-absorber is placed in focal area where reflected radiation from solar concentrator is collected. In the process of designing, parabolic solar concentrators one always seek for the minimum size of the receiver. With small receiver size, one can reduce heat losses as well as cost of whole system. Also small receiver size provides increase of absorbed flux on the surface of receiver. This is the way of obtaining greater efficiency in conversion of solar radiation to heat. In our system, receiver-absorber is cylindrical disk with diameter of 24 mm. It is shown in Fig. 5. Within the solar absorber is placed spiral corrugated pipe through which water flows.

Fig. 6 shows the modified solar receiver with solar spiral corrugated pipe absorber in the next design of my investigations. This is the next solar receiver design concentrator.

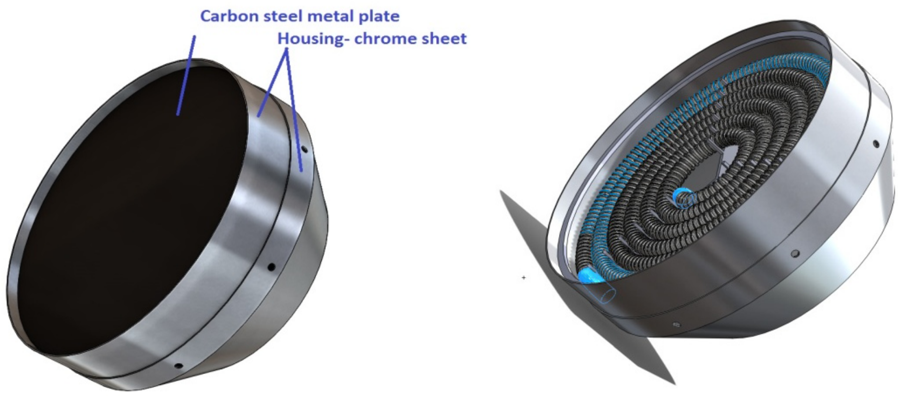
In this paper, only optical properties of receiver are analysed. In our further research, we plan to model all necessary details of receiver's geometry which are important for conversion of solar energy into heat of fluid that is used for transfer energy.

3. Optical Analysis of the Solar Parabolic Dish Thermal Concentrator

For optical analysis of solar parabolic thermal concentrator software TracePro, Lamda Research Corporation, USA is used. First step was importing 3D model designed in CATIA. In TracePro, all material properties are assigned. Twelve trapezoidal reflective petals are defined as standard mirrors with reflective coating. Reflection coefficient was 95%. Receiver was cylinder with diameter 24 mm placed on 1,400 mm from vertex of parabolic dish. Absorbing surface was defined as perfect absorber. After definition of geometry of solar, parabolic concentrator radiation source was defined. Radiation source was circular with diameter same as diameter of parabolic dish (2,800 mm). Radiation source was placed 2,000 mm from vertex of parabolic dish and had circular grid pattern for generating 119,401 rays for Monte Carlo ray tracing. Spatial profile of generated rays was uniform and angular profile was solar radiation. Input parameter for optical analysis is solar irradiance 800 W/m^2. Experiential value for solar irradiation for town of Niš

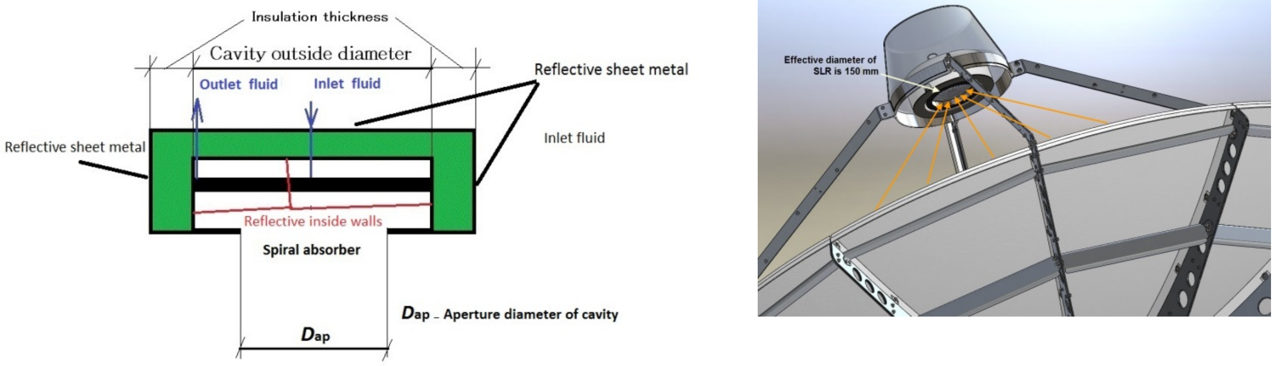
Table 2 Design parameters of solar parabolic dish concentrator.

Parameters	Numerical value	Unit
Aperture radius R_2	1.4	m
Radius of smaller hole R_1	0.025	m
Ideal area of the concentrator A_{idel}	6.208	m^2
The cross section of the opening parabola A_{proj}	6.154	m^2
A sheltered area of the concentrator A_{shadow}	0.000452	m^2
The effective area of the concentrator $A_{ef} = A_{proj} - A_{shadow}$	6.1535	m^2
Receiver diameter	0.20	m
Shape of receiver	Flat circular disc	-
Depth of the concentrator	0.35	m
Focal lenght	1.4	m
ψ_1	10	°
ψ_2	45	°



(a) (b)

Fig. 5 Solar thermal receiver—with flat plate circular disc and without (directly irradiated spiral corrugated pipe absorber).



(a) (b)

Fig. 6 (a) Modified solar cavity receiver for solar parabolic dish concentrating collector and (b) concentrated solar radiation at the focus plane.

in Serbia is between 750 W/m^2 and 900 W/m^2. Optical system for solar parabolic concentrator with traced rays is given in Fig. 7. The optical concentration system consists of three objects: solar parabolic dish reflector, radiation source and receptor (solar receiver) in the focus of the parabolic dish concentrator

Optical analysis is done by generating and calculating Monte Carlo ray trace for 119,401 rays. From all emitted rays, only 103,029 rays reached absorber surface which is 82% rays of emitted rays are

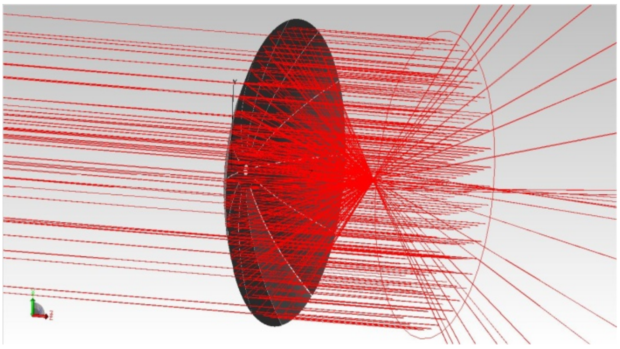


Fig. 7 Optical system of Solar parabolic concentrator with traced rays.

absorbed on receiver. Calculated irradiance for absorbed rays on receiver is from 8.66×10^{-6} W/m^2 to 3.45×10^7 W/m^2.

Total calculated flux on receiver was 4,031 W. In Fig. 8 is shown total irradiance map for absorbed flux on receiver.

From Fig. 8, one can see that, calculated values for total irradiance are in compliance with theoretically values. In the center of receiver, irradiance is from 3.45×10^7 W/m^2 to 2×10^7 W/m^2 and at the periphery of receiver irradiance is from 8×10^6 W/m^2 to 2×10^6 W/m^2.

Irradiance diagram at the center of receiver is given in Fig. 9.

From Fig. 9, one can see that, peak irradiance is in the circle with diameter 8 mm (from -4 mm to 4 mm). Very good irradiance is in the circle with diameter 16 mm. Irradiance diagram at the periphery of receiver is given in Fig. 10.

From Fig. 10, one can see that, irradiance diagram at periphery of receiver is still rather good with peak values of irradiance in the circle diameter 4 mm. Very good values of irradiance is in the circle with diameter 16 mm. From Figs. 9 and 10, one can see that, irradiance has very good values in the circle with diameter 16 mm for center and periphery and that only peak values change from center to periphery.

4. Conclusions

This paper presents optical analysis of the solar parabolic concentrator using the ray—tracing software

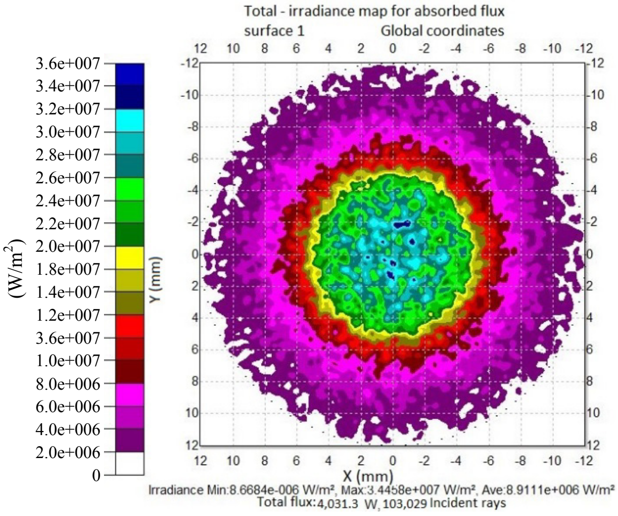


Fig. 8 Irradiance map for absorbed flux on receiver.

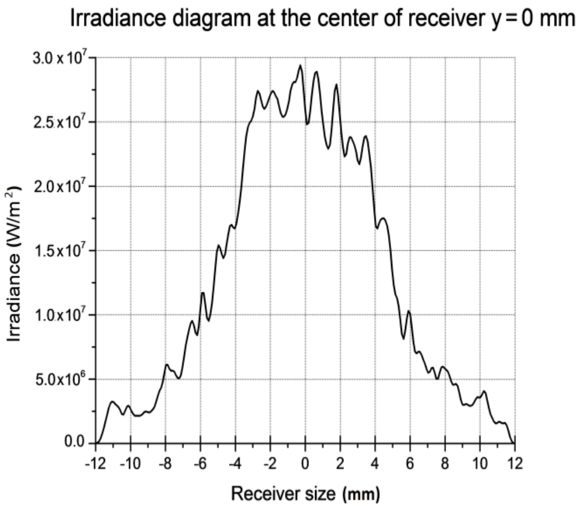


Fig. 9 Irradiance diagram at the center of receiver.

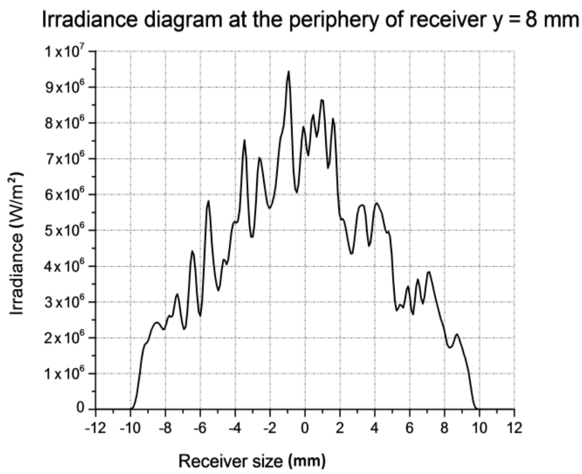


Fig. 10 Irradiance diagram at the periphery of receiver.

TracePro. One can see that, results obtained from optical design of solar parabolic concentrator are satisfactory. Total flux in focal area is good. Irradiance distribution for absorbed flux is relatively uniform for small area for absorber. As a next step, various analysis and simulations of the model are planed. Among others are variation of number of petals, size of petals and shape of petals. In future development of optimization, method is planned. This optimization method will make it possible to find optimal geometrical and optical parameters of the various types of solar parabolic dish concentrators as well as geometrical, optical and thermal parameters of receivers-absorbers.

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References

[1] Badran, A. A., and Yousef, I. A. 2010. “Portable Solar Cooker and Water Heater.” *Energy Conversion and Management* 51 (8): 1605-9.

[2] Joshi, A. S., Dincer, I., and Reddy, B. V. 2011. “Solar Hydrogen Production: A Comparative Performance Assessment.” *International Journal of Hydrogen Energy* 36 (17): 11246-57.

[3] Furler, P., Scheffe, J. R., and Steinfeld, A. 2012. “Syngas Production by Simultaneous Splitting of H_2O and CO_2 via Ceria Redox Reactions in a High-Temperature Solar Reactor.” *Energy & Environmental Science* 5 (3): 6098-103.

[4] Mancini, T., Heller, P., Butler, B., Osborn, B., Schiel, W., Goldberg, V., Buck, R., Diver, R., Andraka, C., and Moreno, J. 2003. “Dish-Stirling Systems: An over View of Development and Status.” *Journal of Solar Energy Engineering-Transactions of the ASME* 125 (2): 135-51.

[5] Mills, D. 2004. “Advances in Solar Thermal Electricity Technology.” *Solar Energy* 76 (1-3): 19-31.

[6] O’Neill, M. J., and Hudson, S. L. 1978. “Optical Analysis of Paraboloidal Solar Concentrators.” In *Proceedings of the 1978 Annual Meeting,* 855.

[7] Imhamed, M. S. A., Tadhg, S. O., Reddy, K. S., and Tapas, K. M. 2013. “An Optical Analysis of a Static 3-D Solar Concentrator.” *Solar Energy* 88 (February): 57-70.

[8] Kaushika, N. D., and Reddy, K. S. 2000. “Performance of Low Cost Solar Paraboloidal Dish Steam Generating.” *Energy Conversion & Management* 41 (7): 713-26.

[9] Ouederni, A. R. E., Ben Salah, M., Askri, F., and Aloui, F. 2009. “Experimental Study of a Parabolic Solar Concentrator.” *Revue des Renouvelables* 12 (3): 395-404.

[10] Rafeeu, Y., and AbKadir, M. Z. A. 2012. “Thermal Performance of Parabolic Concentrators under Malysian Environment: A Case Study.” *Renewable and Sustainable Energy Reviews* 16 (6): 3826-35.

[11] Zhiqiang, L., Justin, L., and Wojciech. L. 2012. “Optical Design of a Flat Solar Concentrator.” *Solar Energy* 86 (6): 1962-6.

[12] Hasnat, A., Ahmed, P., and Khan, K. A. 2011. “Numerical Analysis for the Thermal Design of a Paraboloidal Solar Concentratong Collector.” *International Journal of Natural Sciences* 1 (3): 68-74.

[13] Rebecca, D., Keith, L., Greg, B., and John, P. 2012. “An Experimental Study of Ammonia Receiver Geometries for Dish Concentrators.” *Journal of Solar Energy Engineering* 134 (4): 945-55.

[14] Glen, J., Keith, L., and Andreas, L. 2003. “Optical Performance of Spherical Reflecting Elements for Use with Paraboloidal Dish Concentrators.” *Solar Energy* 74 (2): 133-40.