Ray Tracing Study to Determine the Characteristics of the Solar Image in the Receiver for a Thermal Solar Concentration System

Saša R. Pavlovic PhD student.[*] , **Velimir P. Stefanović** Dr Sci, [*] **Predrag Rajković** Dr Sci, [**] **Emina P. Petrovic** PhD student,[***] **Sadoon Ayed** MSc[****]

[*]Nis. Serbia, Faculty of Mechanical Engineering, Department for Energetics and Process technique, University in Niš, Serbia
[**] Nis. Serbia, Faculty of Mechanical Engineering, Department for Mathematics and Natural Sciences University in Niš, Serbia
[***] Nis. Serbia, Faculty of Mechanical Engineering, Mechatronic and Control Systems, University in Niš, Serbia
[****]University of Technology, Department of Mechanical Engineering, Baghdad ,Iraq,

e-mail : sasap208@yahoo.com, veljas@masfak.ni.ac.rs, pedja.rajk@masfak.ni.ac.rs, smijoc@yahoo.com, sadun_kad@yahoo.com

***Abstract-- This study presents the geometric aspects of the focal image for a solar parabolic concentrator (SPC) using the ray tracing technique to establish parameters that allow the designation of the most suitable geometry for coupling the SPC to absorber – receiver. 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 system has diameter D = 3800 mm and focal distance f = 2260mm. The parabolic dish of the solar system consists from 11 curvilinear trapezoidal reflective petals. For the construction of the solar collectors, mild steel- sheet and square pipe were used as the shell support for the reflecting surfaces. 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 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, polygeneration systems etc*.

Keywords: *ray tracing analysis, optical modelling, thermal solar concentration technology, corrugated Archimedean spiral pipe solar absorber*

I. INTRODUCTION AND SURVEY OF LITERATURE

This paper presents the numerical results of the optimisation of the solar image in a receiver for a fixed absorber in a solar parabolic concentrator, which was a project supported by the Ministry of Education, Science and Technological Development of Republic of Serbia.The device which is used to transform solar energy to heat is reffered to a solar collector. Solar thermal collectors have been widely used to concentrate solar radiation and convert it into medium-high temperature thermal processes. In addition, the list of possible alternative applications of this technology is growing, due to the problems of oil dependency and global warming. 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, 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's 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 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 M. Saleh Ali 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 goal were to design solar concentrator for production of portable hot water in rural India. Their used ray tracing software for evaluation of the optical performance of a static 3-D Elliptical Hyperboloid Concentrator (EHC). Optimization of the concentrator profile and geometry is carried out to improve the overall performance of system. *Kaushika 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 300^0C, when the absorber was placed at the focal point. Cost of their system was US$ 950. *El 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 380^0C.*Y. Rafeeu and M.Z.Z.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 Liu 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.

The decision to make solar parabolic concentrator with 11 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 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 optical and thermal efficiency of concentrating solar collectors.

II. GEOMETRICAL MODEL OF THE SOLAR PARABOLIC CONCENTRATOR AND RECEIVER

The design of the solar parabolic thermal concentrator, and operation are presented. Optical design is based on parabolic dish with 11 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.

The ray tracing technique is implemented in a software tool that allows themodelling of the propagation of light in objects of different media. This modelling requires the creation of solid models, either by the same software or by any computer aided design (CAD) software. Once in the optical modelling software, portions of the rays of the light source propagate in the flow of light, in accordance with the properties assigned to the relevant objects, which may be absorption, reflection, transmission, fluorescence, and diffusion. The sources and components of the light rays, adhering to various performance criteria involving the system parameters, result in simulation of the spatial and angular distribution, uniformity, intensity, and spectral characteristics of the system. Mathematical representation of parabolic concentrator is paraboloid that can be represented as a surface obtained by rotating parabola around axis. Mathematical equations for the parabolic dish solar concentrator in Cartesian and cylindrical coordinate systems is defined as:

$$x^2 + y^2 = 4fz \qquad z = r^2/4f \tag{1}$$

where are 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 know 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 degrees up to 90 degrees. The relationship between the relative aperture and the rim angle is given by:

$$f/D = \frac{1}{4\tan(\psi_{rim}/2)} \tag{2}$$

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 50^0 ($\psi_{rim} = 45{,}6$) is used for cavity receivers while paraboloids with large rim angles are most appropriate for the external volumetric receivers (central receiver solar systems). f/D = 0.59

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.

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

The designed solar parabolic concentrator has geometric concentration ratio $CR_g = 100$.

A. *Parameters Design 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 [11] is used. The calculated coordinates (x and y) for designed parabola are shown in Table I. The calculated values is performed for 22 point in the parabola curve. The equation for parabola is:

$$y = a(x)^2 + b(x) + c \tag{4}$$

The coefficients describing this parabola are:

$a = 1.10526 \times 10^{-4}$

$b = 0$

$c = -2.428275 \times 10^{-14}$

$$y = 1.10526 \cdot 10^{-4} - 2.428275 \cdot 10^{-14} \tag{5}$$

TABLE I COORDINATES OF DESIGNED PARABOLA

X(cm)	-190.0	-158.3	-126.6	-95.00	-63.33	-31.67	0.0
Y(cm)	39.9	27.7	17.78	9.97	4.43	1.12	0.0
X(cm)	31.67	63.33	95.00	126.6	158.3	190.0	-
Y(cm)	1.12	4.43	9.97	17.78	27.7	39.9	-

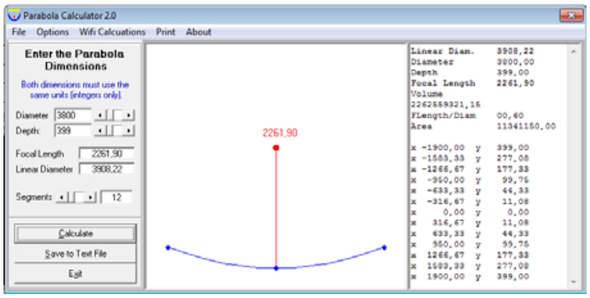

Fig.1. Parabola Calculator 2.0 [11]

Geometrical model of solar parabolic concentrator is parametrically designed from calculated coordinates and it is shown on Fig. 1. Selected model of solar dish concentrator with 11 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 CAD model generation.

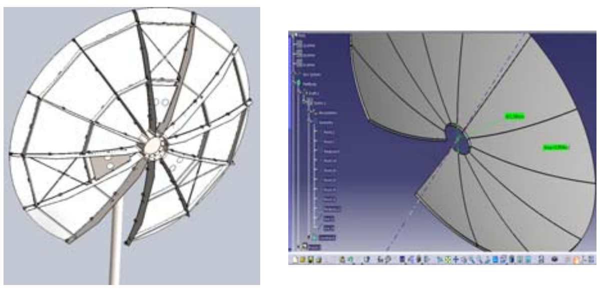

Fig.2 CAD model of solar parabolic concentrator with dimensions and rear view of solar concentration system

Fig.3. 3D CAD model of thermal solar concentration system and sinusoidal profile of corrugated pipe of spiral absorber

A truncated paraboloid of revolution (circular paraboloid) is obtained by rotating the parabola segment about its axis [Fig.4]. Consider a concentrator consisting of 11 trapezoidal reflective petals of identical non-overlapping trapezoidal segments. 3D model of trapezoidal reflective petal of solar parabolic concentrator is presented on Fig. 4. The outer diameter of corrugated pipe is D_e = 12.2 mm, inner diameter D_i = 9.3 mm and thickness of wall pipes is s = 0.25 mm.

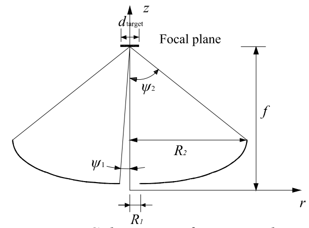

Fig.4 Schematic of truncated parabola

Fig.5 Trapezoidal reflective petal of solar parabolic concentrator

Detailed design parameters of solar parabolic concentrator is given in Table II.

TABLE II DESIGN PARAMETERS OF SOLAR PARABOLIC CONCENTRATOR

Parameters	Numerical value	Unit
Aperture radius R_1	0.2	[m]
Radius of smaller hole R_2	1.9	[m]
Gross collector area A_{gross}	11.82	[m^2]
The cross section of the opening parabola A_{proj}	9.89	[m^2]
A sheltered area of the concentrator A_{shadow}	0.126	[m^2]
The effective area of the concentrator $A_{ef}=A_{proj}-A_{shadow}$	9,764	[m^2]
Receiver diameter	0.40	[m]
Shape of receiver	Corrugated spiral pipe – circular disc	-
Depth of the concentrator	0.399	[m]
Focal lenght	2.26	[m]
ψ_1	6	[^{0}]
ψ_2	45,6	[^{0}]

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 provide 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 Archimedean spiral corrugated pipe type with diameter of 400 mm. It is shown on Fig. 6.

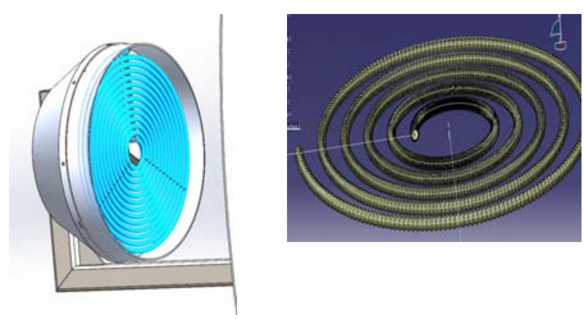

Fig.6. Solar cavity receiver – spiral corrugated pipe type of solar absorber

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.

III. NUMERICAL SIMULATIONS AND RAY TRACING STUDIES TO DETERMINE THE OPTICAL CHARACTERISTICS OF THE SOLAR IMAGE

For optical ray tracing analysis of solar parabolic thermal concentrator software TracePro, Lamda Research Corporation, USA is used. Simulations have been performed using the technique of ray tracing to describe the behaviour of parabolic dish solar concentrators and such simulations have been used to study the behaviour of such concentrators in non – imaging optics; however, there is no such study or simulation of ray-tracing type to describe parabolic solar concentrators. In TracePro all material properties are assigned. 11 trapezoidal reflective petals are defined as standard mirrors with reflective coating. Reflection coefficient was 95%. Receiver was cylinder with diameter 400 mm placed on 2075 mm from vertex of parabolic dish (optimal focal distance from vertex of parabolic solar concentrator). 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 (3800 mm). Radiation source was placed 2000 mm from vertex of parabolic dish and had circular grid pattern for generating 119401 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 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.

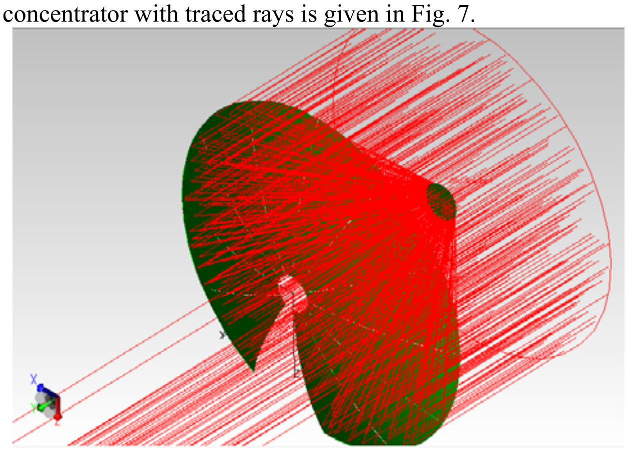

Fig.7. Optical system of solar parabolic concentrator with traced rays

Optical analysis is done by generating and calculating Monte Carlo ray trace for 119401 ray. From all emitted rays only 103029 rays reached absorber surface which is 82% rays of emitted rays are absorbed on receiver. Calculated irradiance for absorbed rays on receiver is from $1.74 \cdot 10^{-8}$ W/m^2 to 62100 W/m^2. Total calculated flux on receiver was 7800W. On Fig. 8 is shown total irradiance map for absorbed flux on receiver. When the sunlight shines on the solar collector including the direct and scattered radiation, there are three conditions affecting on the absorption properties of the solar collector: (1) direct solar radiation absorbed directly by the solar collector and the light energy after the specular reflection; (2) the light energy of the scatter solar radiation after the diffuse and specular reflection; (3) the light energy of the direct solar radiation after the diffuse reflection. The slope of incident light is different in different latitude and time, so we deal it with integral processing in the range of incident angle.

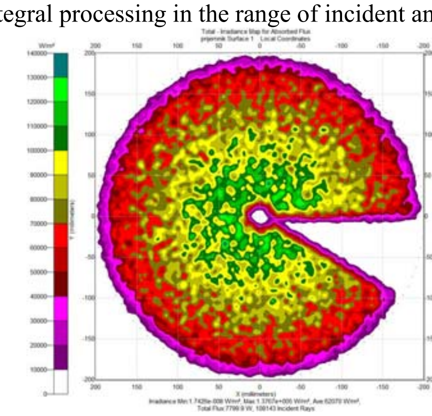

Fig.8. Irradiance map for absorbed flux on spiral receiver (solar focal image)

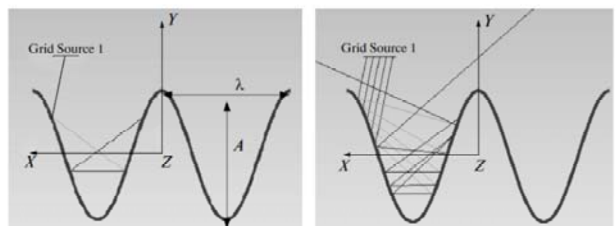

Fig.9. Schematic diagram of optical path shinning on the sinusoidal corrugated pipe absorber

We take city of Nis (Laboratory for Solar Thermal Engineering) as an example. Nis is located in southeast Serbia longitude 43.30° North latitude and 21.90 east longitude. According to the declination angle δ (–23.45°on winter solstice), sunset hour angle ω, altitude of the sun *h*, the installation angle of 45° and the North − south placement of solar parabolic collector. In order to calculate the angle of incidence, the sun angle is defined as follows:

$\delta = 23.45\sin\varepsilon$, $\varepsilon = 2\pi d/365$, $\phi = 21.90^0$, $\omega = 15t$

$\sin h = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega$

$\sin\mu = \frac{\sin\omega\cos\delta}{\cos h}$, $\cos i = \cos\theta\sin h + \sin\theta\cosh\cos\mu$,

where *d* is the number day of 365, *t* is the time in hours.

TABLE III CALCULATION RESULTS IN NIS

Time	Sunset hour angle [ω]	Altitude of the sun *h*	Angle of incident *i*
9:00	-45^0	18^0	55^0
10:00	-30^0	25^0	45^0
11:00	-15^0	30^0	37^0
12:00	0^0	32^0	34^0
13:00	15^0	30^0	37^0
14:00	30^0	25^0	45^0
15:00	45^0	18^0	55^0

The influences of absorption rate for the sinusoidal corrugates absorber plate by aspect ratio and the slope of incident light are plotted in Fig. 10. From the optical point of view, the times of light reflection absorption increases with the aspect ratio, which causes the absorption rate of the absprber plate increasing. Specially, the absorption rate is close to 1, when the aspect ratio tends to infinity.

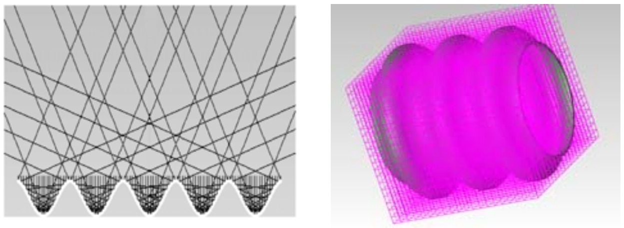

Fig.10. Ray tracing and radiation control volume grid (1000 elements) for part of corrugated pipe

According to the boundary conditions, the optical properties can be obtained after many simulation calculations, which is called the ray tracing method [11].

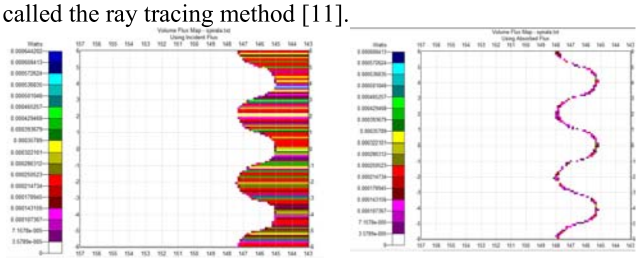

Fig. 11. Volume radiation flux distribution (incident and absorbed flux)

Figure 12. shows scattered model for reflection of incidence angle for solar parabolic dish concentrator with 11 curvilinear trapezoidal reflective petals. In general, the reflectance of a surface increases with angle of incidence. But for a mirror, the reflectance is already very high when the AOI = 0 deg. It can't increase much more. This is why the peak BRDF doesn't change with AOI. However, the reflectance of a black surface increases with AOI, no matter how black the surface.

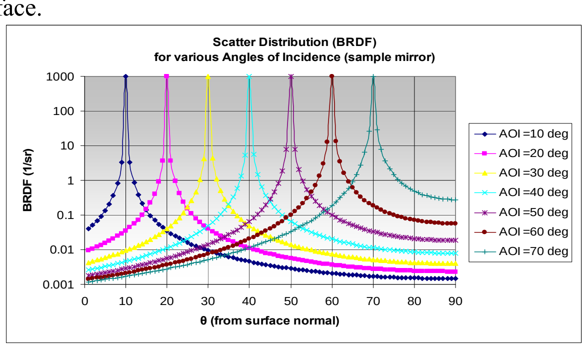

Fig. 12. ABg giving the BRDF as a function of incidence angle

CONCLUSIONS

This paper presents optical analysis of the solar parabolic concentrator using the ray - tracing software 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. A detailed simulation and analysis was conducted to evaluate the absorption rate of sinusoidal_corrugated absorber pipe. Lights with arbitrary incident angle shinning on the sinusoidal_corrugates absorber plate can occur second times of reflection, part of the light have third times and more reflection. 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 different types of solar cavity receivers - absorbers.

ACKNOWLEDGMENT

This paper is done within the research framework of research projects: III42006 – Research and development of energy and environmentally highly effective polygeneration systems based on renewable energy resources. Project is financed by Ministry of Education, Science and Technological Development of Republic of Serbia. Authors acknowledge to Lambda Research Corporation for allowing to use software TracePro for PhD Thesis research of SašaPavlović.

REFERENCES

[1] Badran, A.A.Yousef,I.A.,et al.,"Portable solar cooker and water heater", *Energy Conversion and Management* 51 (8), 1605–1609, 2010.
[2] Joshi,A.S.,Dincer,I.,Reddy, B.V., "Solar hydrogen production: a comparative performance assessment", *International Journal of Hydrogen Energy* 36(17),11246–11257, 2011.
[3] Furler, P.,Scheffe,J.R.,Steinfeld,A., "Syngas production by simultaneous splitting of H_2O and CO_2 via ceria redox reactions in ahigh-temperature solar reactor", *Energy & Environmental Science* 5(3),6098–6103,2012.
[4] Mancini,T.,Heller,P.,Butler,B.,Osborn,B.,Schiel,W.,Goldberg,V.,Buck, R.,Diver,R.,Andraka,C.,Moreno,J.."Dish–Stirling systems:an over view of development and status",*Journal of Solar Energy Engineering-Transactions of the ASME* 125(2),135–151, 2003.
[5] Mills,D. "Advances in solar thermal electricity technology", *Solar Energy* 76 (1–3),19–31, 2004.
[6] O'Neill, M. J. and Hudson, S. L. "Optical Analysis of Paraboloidal Solar Concentrators." *Proceedings 1978 Annual Meeting, U.S. Section of Int. Solar Energy Society*, August 1978; Denver, CO. Vol. 2.1: p.855
[7] Imhamed M. Saleh Ali, Tadhg S. O'Donovan , K.S. Reddy, Tapas K. Mallick, "An optical analysis of a static 3-D solar concentrator, " *Solar Energy* 88, 57-70, 2013.
[8] N.D.Kaushika, K.S.Reddy,"Performance of low cost solar paraboloidal dish steam generating," *Energy Conversion & Management* 41, 713-726, 2000.
[9] A.R.El. Ouederni, M. Ben Salah, F.Askri and F. Aloui, "Experimental study of a parabolic solar concentrator, *Revue des Renouvelables* ,Vol. 12, 395-404, 2009.
[10] Rafeeu, M.Z.A.AbKadir, "Thermal performance of parabolic concentrators under Malysian environment,": A case study, *Renewable and Sustainable Energy Reviews*, 16, pp. 3826-3835, 2012.
[11] Zhiqiang Liu, Justin Lapp, Wojciech Lipinski, "Optical design of a flat solar concentrator, *Solar Energy 86*, pp. 1962-1966, 2012.
[12] http://mscir.tripod.com/parabola/
[13] Lubos Mitas, Quantum Monte Carlo, J. Current Opin ion Solid State Mater. Sci., 1997, vol. 6, no. 2, pp. 696–700.