OPTICAL ANALYSIS AND PERFORMANCE EVALUATION OF A SOLAR PARABOLIC DISH CONCENTRATOR

by

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In this study, the optical design of a solar parabolic dish concentrator is presented. The parabolic dish concentrator consists from 11 curvilinear trapezoidal reflective petals made of polymethyl methacrylate with special reflective coating. The dish diameter is equal to 3.8 m and the theoretical focal point distance is 2.26 m. Numerical simulations are made with the commercial software TracePro from Lambda Research, USA, and the final optimum position between absorber and reflector was calculated to 2.075 m; lower than focus distance. This paper presents results for the optimum position and the optimum diameter of the receiver. The decision for selecting these parameters is based on the calculation of the total flux over the flat and corrugated pipe receiver surface; in its central region and in the peripheral region. The simulation results could be useful reference for designing and optimizing of solar parabolic dish concentrators as for as for CFD analysis, heat transfer and fluid flow analysis in corrugated spiral heat absorbers.

Key words: *paraboloid dish concentrator, ray tracing analysis, TracePro software, spiral geometry, scheme macro language*

Introduction and survey of literature

Solar collector is the device that transforms solar energy into useful heat. These devices are able to concentrate solar radiation and convert it into low, medium or high temperature thermal processes. With the threats of global warming and the increased energy demand worldwide, the use of renewable energy sources is becoming more and more attractive. Characteristics of solar thermal collectors, especially the concentrating type, are well-established in research literature. Many applications use solar collectors, as industrial processes, electricity plants and water heating systems for covering the domestic water demand in buildings. The solar concentrating collectors operate by focusing solar beam radiation onto a small area known as the focal area. Many classes of concentrating collectors are available, each with different concentrating ratio and maximum absorber temperature, depending on the type of application. Generally, solar thermal utilization is separated into low-temperature solar systems and high-temperature solar concentrating systems. Pavlović *et al.* [1] has investigated the op-

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timal geometric parameters of a dish solar thermal concentrator using Monte Carlo ray tracing method. This paper presents results for the optimal position and diameter of the receiver. The decision for choosing the optimal position and diameter of the receiver is based on calculation of the total flux on the receiver surface, on the center and on the periphery of the receiver. The low manufacturing cost, the two-axis tracking solar system and the design with flat mirror system (Solarux CSP) are its advantages, which are described in this paper. Moreover, this paper has been focused on air-conditioning, heating, and producing electricity by using Solarux CSP. The aim of this system is to use planar mirrors instead of parabolic mirrors in order to reduce the cost and to design a system that can be manufactured easily by every kind of terrain (rocky, plain, *etc.*) and can be used by developing countries [2]. The low temperature solar systems (FPC and ETC), which may not involve sunlight concentration, have lower conversion efficiency. The high temperature solar thermal systems (PTC, CPC, Dish, Fresnel), which require sunlight concentration, have higher conversion efficiency [3, 4]. Pavlovic *et al.* [5] presented a mathematical and physical model of the new offset type parabolic concentrator and a numerical procedure for predicting its optical performance. The designed parabolic concentrator is a low cost solar collector for medium temperature applications. Pavlović *et al.* [6] developed mathematical model of solar parabolic dish concentrator based on square flat facets applied to polygeneration systems. Authors developed an optimization algorithm for determining the optimum geometric, optical and cost parameters.

Traditionally, the optical analysis of solar concentrators is carried out by computer ray-trace programs. This calculating method is fast and accurate but assumes that the radiation source is a uniform disk. Ali *et al.* [7] have presented a study that aims to develop a 3-D static solar concentrator that can be used as low cost and low energy substitute. Their goal was to design solar concentrators for production of portable hot water in rural India. Kaushika and Reddy [8] used an aluminum frame satellite dish with diameter of 2.405 m as reflector to reduce the weight of the structure and the cost of the solar system. In their system, the average water/vapor temperature was 300 °C, when the absorber was placed at the focal point. The cost of the examined system was estimated about 1000 US$. Ouederni *et al.* [9] tested a parabolic concentrator of 2.2 m diameter with 85% reflectance and they concluded that the average temperature in their system was approximately 380 °C. Rafeeu and Ab-Kadir [10] presented a simple study in designing, manufacturing and testing small laboratory scale parabolic concentrators. They made two dishes from acrylonitrile butadiene styrene and one from stainless steel. Li *et al.* [11] presented a procedure to design a facet concentrator for a laboratory-scale research on medium-temperature solar applications. Qianjun *et al.* [12] has investigated on the photo-thermal conversion efficiency in order to improve the cost effectiveness of the examined solar system. They used the Monte Carlo ray tracing method for calculating the radiation flux distribution on the receiver and the ANSYS Fluent for calculation of radiation and convection heat transfer mechanisms. Their results proved that the maximum energy efficiency was about 52% when the direct normal irradiation was 800 W/m^2. Eswaramoorthy and Shanmugam [13] investigated the thermal efficiency of solar a cooker with parabola diameter of 3.56 m and total aperture of 10.53 m^2, with a finally thermal efficiency of 60%. Reddy *et al.* [14] have experimentally investigated a solar parabolic dish collector with 20 m^2 aperture in order to investigate its performance with the examined modified cavity receiver. The average value of the overall heat loss coefficient was found to be about 356 W/m^2. Jones and Wang [15] computed the flux distribution on a cylindrical receiver of parabolic dish concentrator using geometric optics method. Parameters such as concentrator surface errors, pointing offset errors and finite sun shape were taken into consideration in the geometric optics method. Thakkar *et al.* [16] have investigated the possible use of parabolic dish collector in process industries. They presented a mathematical model for heating application using thermal oil. Blazquez *et al.* [17] described optical test for the DS1 (parabolic Stirling dish) prototype, a study that was carried out by CTAER. The aim of this investigation was to characterize the optical parameters of DS1 prototype. The results comparison proved that the dish surface had an average optical error of 2.5 mrad and an estimated spillage value of 7%, for the examined geometry. Li *et al.* [18] presented the radiation flux distributions of the concentrator-receiver system by Monte Carlo ray tracing. The final radiation flux profiles were subsequently transferred to a CFD code as boundary conditions in order to simulate the fluid flow and the conjugated heat transfer in the receiver cavity by coupling the radiation, natural convection, and heat conduction numerically. Pavlović *et al.* [19, 20] presented an optical design and ray tracing analysis of a solar dish concentrator composed of 12 curvilinear trapezoidal reflective facets made from solar mirror with silvered coating layer. The goal of this paper was to present the 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.* As it stated in the previous paragraph, 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 [21]. Their method for calculating the optical performance is fast and accurate but assumes that the radiation source is a uniform disk. For successfully operation, the dish solar collector system, the optimal design of the receiver and the heat flux distributions are very important parameters that should be known [22-25].

In this paper, two types of the parabolic dish receivers have been analyzed. One is the flat dish receiver and the other a spiral coil receiver. The optimal parameters of this receiver have been defined after making a sensitivity analysis with two parameters: the receiver position and the receiver diameters. For each study case, the total energy delivered to the receiver and the average heat fluxes are calculated. This design reduces dramatically the system cost, while allows concentration ratios suitable for medium and high temperature level applications. The reason for the lower cost is based on the use of small parts which can be easily fabricated. If the reflector were a continuous dish, then its construction and its installation would be difficult with the respective increase in the cost. The dimensions of reflecting surface (diameter and focal length) are determined by desired power, taking into consideration the maximum levels of direct normal radiation and the respective thermal efficiency of collector.

Geometrical model of solar parabolic dish concentrator

The mathematical representation of the examined solar parabolic dish concentrator is a paraboloid that can be represented as a surface obtained by rotating a parabola around axis [1]. The model of the parabolic concentrator is designed with 11 curvilinear trapezoidal reflective petals, because in the position of the 12th there is the bracket. The geometrical model of the segmented solar reflector with corrugated spiral coil absorber is shown in figs. 1(a-c).

The general mathematical formula for the paraboloid is given from the following equation:

$$x^2 + y^2 = 4fz \tag{1}$$

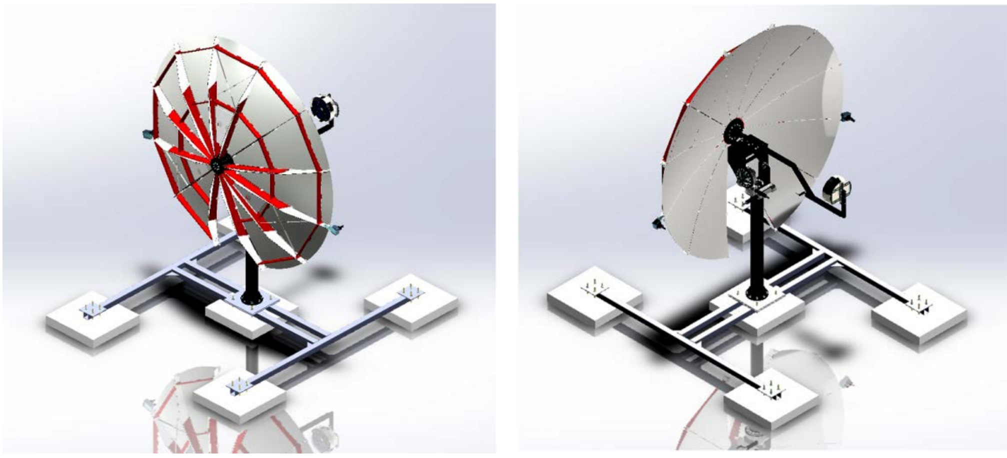

Figure 1. Parabolic dish segmented reflector with corrugated coiled heat absorber

Usually, the paraboloids used in solar collectors have rim angles from 10° up to 90°. The paraboloids with small rim angles have the focal point and receiver at large distance from the surface of the concentrator. Paraboloids with rim angle smaller than 50° are used for cavity receivers, while paraboloids with large rim angles are most appropriate for the external volumetric receivers (central receiver solar systems).The examined parabolic solar concentrator has its rim angle, ψ_{rim}, equal to 45.6° and its focal to diameter ratio equal to 0.59. The model of the solar parabolic concentrator is very complex and has a large number of elements that ensure proper positioning of the system at any point of time. This model of solar parabolic dish concentrator provides maximum concentration of solar radiation in the receiver at any point of time with minimal optical losses. After finishing the system, experiments will be made in the solar laboratory of Faculty of Mechanical Engineering in Nis, Serbia. The next step will be a validation between numerical and experimental results. Moreover, this study presents results which will aid to the final design of the system, in order to achieve maximum experimental performance. It is important to state that the total cost of the collector is about 7000 euros. Design parameters of the solar parabolic dish concentrator are included in tab. 1.

The main objectives of the receiver design were to:

- maximize the solar energy delivered to the absorber,
- maximize the efficiency coefficient of the heat exchange process,
- make the receiver to be able to perform in a wider and higher temperature range,
- make compact and light receiver to ensure minimal mechanical load to the construction of solar concentrator, and
- make simple construction to ensure low production costs and maintenance.

The shape of the receiver depends on its dimensions and mainly to the concentrator focal length and the rim angle. Since the rays of the sun that reach to the concentrator are not parallel due to the finite angular size of the sun's disc and the parabolic dish surface is not ideal, the distribution of reflected rays across the focus forms an image of finite size centered close to the focus. Photo-thermal conversion in a dish cavity receiver is a key process to utilize efficiently solar energy, mainly because the cavity receiver converts the collected solar radiation into thermal energy by coupling complicated heat transfer phenomena.

Table 1. Design parameters of the solar parabolic dish concentrator

Parameters	Numerical value	Unit
Concentrator aperture diameter	3.8	[m]
Concentrator aperture area	10.28	[m^2]
Surface area of parabolic dish	21.39	[m^2]
Focal-diameter ratio	f/D = 0.59	[–]
Direct normal insolation	DNI = G_0= 800	[Wm^{-2}]
Flat circular absorber diameter	dr_1 =0.2; dr_2 = 0.3; $dr_{3\text{opt}}$ = 0.4	[m]
Receiver type 1	Circular flat plate absorber	[–]
Receiver type 2	Spiral corrugated heat absorber	[–]
Reflectivity of segmented petals	0.98	[–]
Focal distance	$f_{\text{theorethical}}$ = 2.26	[m]
R_1	0.2	[m]
R_2	1.9	[m]
θ_{sun}	$4.65 \cdot 10^{-3}$	[rad]
ψ_1	5.06	[°]
ψ_2	45.6	[°]
Depth of the concentrator	0.399	[m]

In this paper, two types of receivers are investigated: flat plate receiver and receiver with spirally coiled pipe with transverse circular corrugation. Flat plate receiver, fig. 2(a) has the circular flat absorber surface as the entrance to cavity. The diameter of the absorber is designed to capture the radiation from the concentrator. The circular flat absorber can be made from stainless steel painted in black. Figure 2(b) illustrates the cross section of that flat plate cylindrical cavity receiver. The circular flat plate at the entrance of the cavity receiver and the spiral pipe absorber where the working fluid flows, are shown in this figure. The main reason for positioning circular flat plate in entrance of the cavity is the increase of the receiver's thermal efficiency and decrease of thermal losses. In the examined system, the circular flat plate receiver had diameter equal to 400 mm and is made from copper.

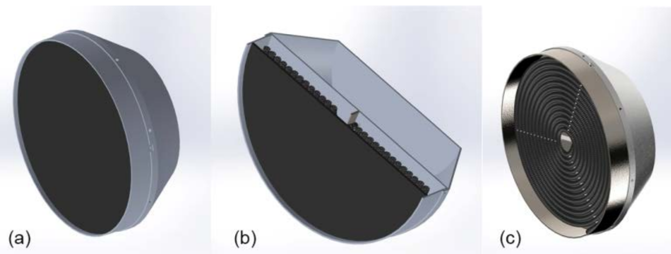

Figure 2. (a) Cavity receiver with flat circular disk absorber, (b) cross section of cylindrical cavity receiver with flat circular disk, and (c) cross section of cylindrical cavity receiver with corrugated coiled heat absorber

The second type of receiver is cylindrical cavity receiver, made from aluminum, with corrugated coil absorber directly exposed to the concentrated solar radiation. The pattern of the spiral is the Archimedean spiral. Figure 2(c) depicts the cross section of this type of receiver. The main characteristic of corrugated coil absorber is that only half of the absorber is exposed to the concentrated solar radiation. In order to obtain the best ratio between active surface and total volumen of absorber Archimedean spiral is chosen, which geometry is described by eqs. 2 and 3.

$$x(t) = \left(0.4 - 0.35\frac{t}{26\pi}\right)\cos(t) \tag{2}$$

$$y(t) = \left(0.4 - 0.35\frac{t}{26\pi}\right)\sin(t) \tag{3}$$

This spiral has the following good characteristics:

– it is compact and can be easily and cheaply produced, and
– it has greater convective heat transfer.

Designing 3-D model of the spiral coil in CAD software is a very demanding task, thus authors decided to develop mathematical model for the Archimedean spiral coil and implement it in the Scheme macro language. The scheme macro language is LISP type programming language used in program TracePro for extending standard capabilities of program TracePro and solving highly specialized problems. With the developed program in the Scheme macro language, we had possibility to automatically design various spiral coil receivers. After examination of several possible spiral coils we decided that the most convenient spiral coil for our receiver is the spiral coil made of stainless steel AISI 304 with dimensions presented in tab. 2. Usually in this type of receivers, the working fluid (pressurized water, thermal oil, air, propylene glycol) circulates inside the tube, entering from the rim and leaving at the center where the radiation intensity and temperature are higher. To avoid pipe deformations, the receiver has a small hole in the center, of about 50 mm in diameter.

Table 2. Geometrical parameters of spiral coil receiver

d_i [mm]	9.3	inside diameter of pipe
d_0 [mm]	12.2	outside diameter of pipe
δ [mm]	0.25	pipe wall thickness
R_{min} [mm]	25	minimum radius of the coil
R_{max} [mm]	202	maximum radius of the coil
p_0 [mm]	13.6	spiral coil pitch
n [–]	13	number of coil turns

Numerical ray tracing simulations to determine the optimal concentrating characteristics of the solar parabolic collector

For optical ray tracing analysis of the solar parabolic thermal concentrator, software TraceProis used. The input parameters for all the simulations are the following.

– Eleven trapezoidal reflective petals are defined as standard mirrors with the coefficient of reflection 0.95.
– Absorbing surface of the receiver is defined as perfect absorber.
– Irradiance 800 W/m^2.
– Radiation source is defined as a virtual window to a distant source with parallel rays emanating as if from a window; position of the radiation source is 2500 mm from the vertex of parabolic reflecting surface, in order to be above the focal point.

– Radiation source is defined as circular ray pattern with diameter same as diameter of parabolic dish (3800 mm); number of rays traced was 119401.
– In TracePro software Monte Carlo ray tracing is used; uniform spatial profile and solar angular profile is used (equivalent to a solar dish of 0.26 degree half angle); uniform flux and weighted angle is used.
– Wavelength is 0.5461 μm.

The first step in analysis is the determination of the theoretical focal point distance. The examined solar dish concentrator had focal point distance equal to 2260 mm. The spot diameter of receiver was 28 mm. The average irradiance at this small receiver surface was $1.21 \cdot 10^7$ W/m^2. The total flux (total power or solar concentrated incident power) on the receiver was 7507.1 W. The maximum radiant density flux at small spot diameter (theoretical focal spot diameter) was $2.56 \cdot 10^7$ W/m^2.

Theoretical focal point distance of 2260 mm was not adequate because spot diameter was only 28 mm. For such small receiver diameter there would be high temperature level. For this reason, several numerical simulations were done to determine the optimal position and size of the receiver. For these simulations, receiver was a flat circular disk with diameter of 400 mm. Position of the receiver (measured from the vertex of parabolic reflecting surface) was varied from 1900 m to 2300 mm with step size 50 mm. The total flux (total absorbed power of incoming solar radiation) and the average irradiance as a function of the distance from the vertex of the parabolic reflecting surface to the receiver position are presented in figs. 3 and 4, respectively.

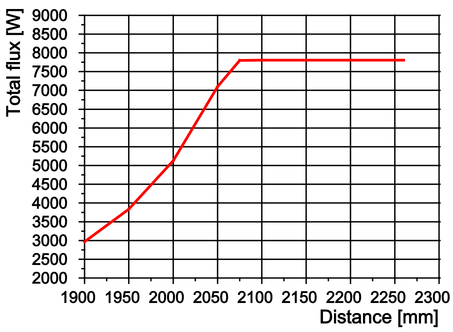

Figure 3. Total flux as a function of receiver position

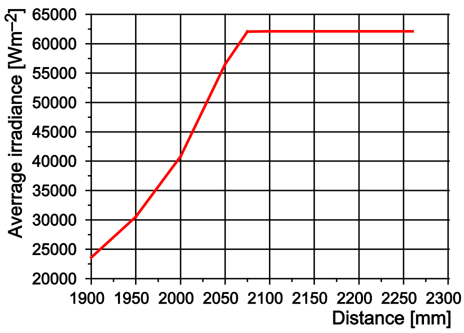

Figure 4. Concentrated solar radiation received by the receiver as a function of its position

It is obvious from figures 4 and 5 that the optimum position for the flat circular receiver is 2075 mm measured from the vertex of the parabolic reflecting surface. At this distance, the total flux was 7799.99 W and average irradiance was 62070 W/m^2. The total flux and the average irradiance was rising from receiver's position on 1900 mm till receiver's position on 2075 mm because the focal area diameter was greater than receiver's diameter. At the 1900 mm position, the focal area diameter was 740 mm and receiver's diameter was 400 mm. At the optimum position of 2075 mm the focal area diameter is 400 mm, while the total flux and the average irradiance have optimal values. For positions greater than 2075 mm, the focal area diameter was smaller than receiver's diameter and the total flux and the average irradiance have constant values. In figs. 5 and 6 the maximum irradiance and the average irradiance as a function of the focal area diameter are presented, respectively. It should be considered here that the ordinate axis is on the logaritmic (log10) scale. This was necessary because of the huge differences in values for the maximum irradiance and the average irradiance. At the theoretical focal point distance (2260 mm) focal area diameter was only 28 mm and at the position of 1900 mm, the focal area diameter was 740 mm. At the theoretical focal point distance the maximum irradiance was $2.56 \cdot 10^7$ W/m^2 and at the position 1900 mm the maximum concentrated irradiance was 38558 W/m^2.

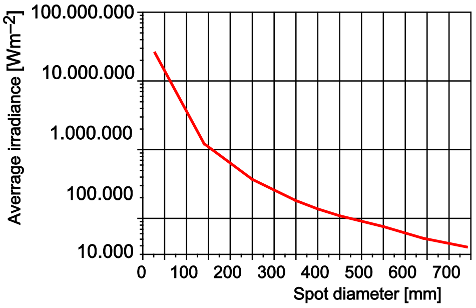

Figure 5. Maximum irradiance as a function of focal area diameter

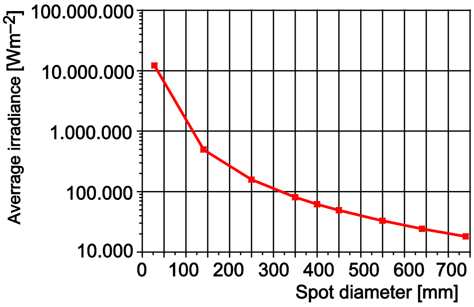

Figure 6. Average irradiance as a function of focal area diameter

After a successful determination of the optimum position for the receiver location, the next step was to define the optimum reciever's diameter. Several numerical simulations were performed for receiver diameter from 100 mm to 400 mm with step size 30 mm. For each numerical simulation the total flux and the average irradiance were calculated. The values of the total flux and of the average irradiance are the deciding factors for selecting the optimum size of the receiver. The optical concentration ratio as a function of the receiver diameter is depicted in fig. 7. The optical concentration ratio in solar concentrators represents a compromise between their optical and thermal performance. The examined parabolic solar collector optimum value of the optical concentration ratio was 77.86 for the receiver with 400 mm diameter. Figure 8 illustrates the geometrical concentration ratio. Similar reasoning is true for the geometrical concentration ratio. The optimal value for the geometrical concentration ratio was 81.84 for the receiver with 400 mm diameter.

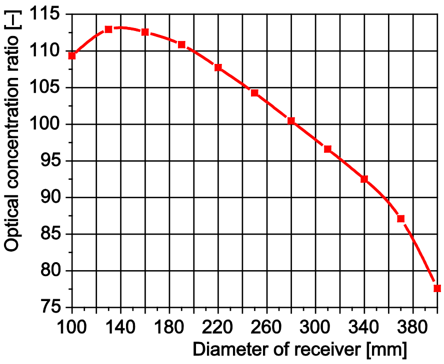

Figure 7. Optical concentration ratios as a function of receiver diameter

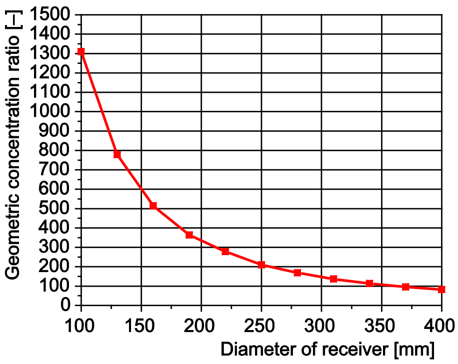

Figure 8. Geometrical concentration ratios as a function of receiver diameter

Figure 9 displays the total flux as a function of the receiver diameter. It is obvious that the larger receiver means that receiver captures the incoming solar radiation with a better way. The maximum total flux value was 7799.9 W for the receiver with 400 mm diameter. Figure 10 shows the optical efficiency as a function of the receiver diameter. For the optical efficiency, similar reasoning is correct. Larger receiver means better capture of the incoming solar radiation, so the total flux and the optical efficiency are higher. The maximum value for the optical efficiency was 0.95 for receiver with 400 mm diameter.

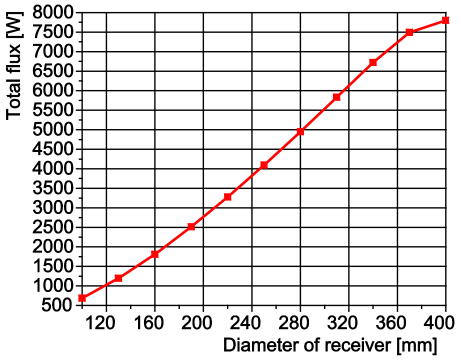

Figure 9. Total flux as a function of receiver diameter

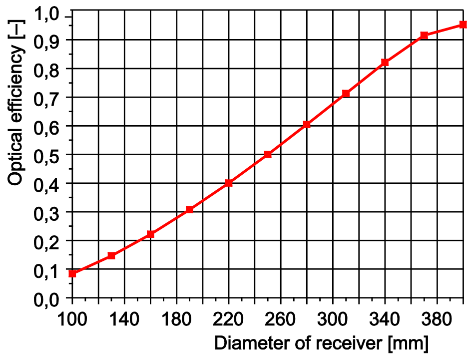

Figure 10. Optical efficiency as a function of receiver diameter

Comparison of optical performances of flat and corrugated coil absorber

For comparing the optical performances of flat and corrugated coil absorber, software TracePro from Lambda Research Corporation USA is used. Figure 11 shows the distribution of the irradiance along the receiver's diameter. Received irradiance by the receiver for flat absorber is displayed with green line and irradiance for corrugated coil absorber is displayed with red line. It is obvious that the red line is wavy and this is because corrugated coil absorber consists from 13 coils. Irradiance for corrugated coil absorber is smaller than for flat absorber because of complicated geometry of corrugated coil absorber. The vacuums in the spiral let a part of the solar irradiation to pass through the spiral absorber and the intercept factor is lower.

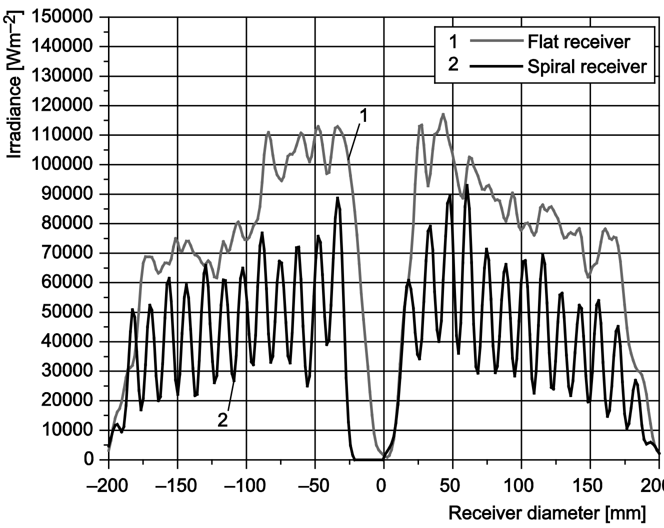

Figure 11. Irradiance for flat and corrugated coil absorber

Total flux, minimum, maximum and average irradiance for flat absorber and corrugated coil absorber is displayed in tab. 3.

Table 3. Optical properties for flat and corrugated coil absorber

		Flat absorber	Corrugated coil absorber
Total flux	[W]	7800.3	7244.9
Minimum irradiance	[Wm^{-2}]	$1.8681 \cdot 10^{-9}$	$4.5188 \cdot 10^{-9}$
Maximum irradiance	[Wm^{-2}]	131390	98584
Average irradiance	[Wm^{-2}]	62073	14641

Solar energy measurement and validation

All the numerical simulations are based on constant value of irradiance (800 W/m^2). This value was chosen because it correspondents to the average irradiance for town of Nis. We decided to measure global solar radiation for several hours in order to see if our chosen values respond to the changing solar radiation during day. After measuring global solar radiation, we also measured the diffuse radiation. To obtain the direct component of solar radiation we set shadow band above pyranometer. If the pyranometer rotates with the solar tracker, you have to deduct diffuse hemispherical irradiance (DHI) from global hemispherical irradiance (GHI), where DI is measured with a shaded pyranometer which must also be on the tracking system: DNI = GI (on tracker) − DI (on tracker). Measurements are done on the roof of solar laboratory of Mechanical Engineering Faculty, University of Nis. Authors have chosen a clear and sunny day (18th September 2015, from 9 a. m. till 4:40 p. m.) for measurements. Measurements are done with the pyranometer Kipp & Zonen CM11 (shown in fig. 12). The basic technical characteristics of the pyranometer Kipp & Zonen CM11 are:

Figure 12. Pyranometer Kipp&Zonen CM11

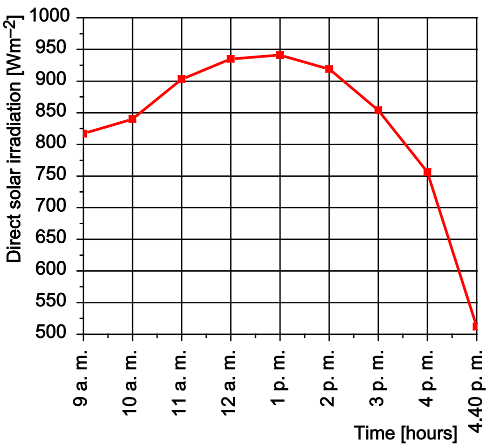

Figure 13. Direct normal irradiance as a function of time

– radiation measurement range is 0÷1400 W/m^2 (max. 4000 W/m^2),
– spectral range is 305-2800 nm, and
– sensitivity is 4-6 μV/(W/m^2).

The maximum relative error in measuring of the total solar radiation was $\Delta G/G$ = 3%. The pyranometer measures the incident solar radiation from all directions (2π steradian) in the hemisphere above the plane of the instrument. The measurement is the sum of the direct and the diffuse solar irradiation and it is called as global solar irradiance. Figure 13 illustrates direct normal irradiance (DNI) as a function of time. It is shown that DNI is greater than 800 W/m^2 for period from 9 a. m. till 3 p. m. hours. For 9 hours, DNI was 817 W/m^2 and for 15 hours DNI was 854 W/m^2. After 3 p. m., the pyranometer came in the shadow of cage in which all laboratory equipment is placed. This is explained by the rapid decline of DNI after 15 hours.

The variation of total heat flux and of average irradiation is shown in figs. 14 and 15, respectively. The shape of these curves is similar, fact that proves the direct relation between these parameters.

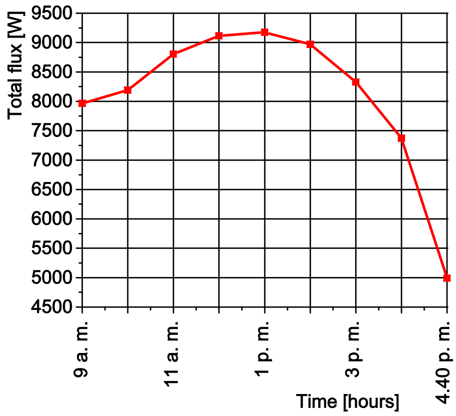

Figure 14. Total flux as a function of time

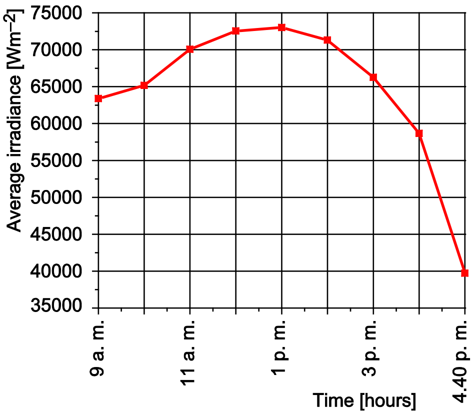

Figure 15. Average irradiation as a function of time

Discussion

In this study an optical optimization of a parabolic dish concentrator is presented. The main optimization parameter is the distance between the absorber and the reflector and finally the optimum position was found to be lower than the focal distance. This result is very important and can be utilized in the future for designing similar concentrated systems. Moreover, two different receivers are tested in order to compare their optical efficiency. The flat circular disk plate has greater performance that the corrugated coil absorber because the second has not a continuous surface. However, the final results proved that these absorbers give similar results; something that proves the satisfying performance of the spiral coil absorber. In the final part of this study, measurements for the Nis are presented in order to validate the hypothesis of the value of 800 W/m^2 for the direct solar irradiation in the simulations with TracePro. This solar potential is high enough for utilizing this collector in medium and high temperature applications.

Conclusion

The optical design of a solar parabolic dish concentrator is presented. The examined parabolic dish concentrator consists from 11 curvilinear trapezoidal reflective petals made of PMMA XT (polymethyl methacrylate) with special reflective silvered coating. The concentrator diameter is 3.8 m and the theoretical focal point distance 2.26 m. The innovative point of this study is the optical comparison between a flat circular disk and a corrugated coil receiver. Numerical simulations are carried out with the commercial software TracePro from Lambda Research, USA. The optimum position of the receiver is 2.075 m measured from the vertex of parabolic reflecting surface. The optimum diameter of the receiver is 400 mm. The flat disk, which is the theoretical optimum absorber optically, performs better at about 8%, a small difference which proves the high performance of the spiral absorber. Moreover, the measurements proved that the DNI in city of Nis is close to 800 W/m^2, fact that validates the selected value in the simulation. In real system, which is in final stage of construction, the receiver will have cylindrical shape and inside the cylinder cavity there will be a spiral corrugated pipe from stainless steel AISI 304. After constructing this system, experiments will be done on the roof of the solar laboratory of Faculty of Mechanical Engineering, University of Nis, Serbia.

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Nomenclature

D – diameter of parabola, [m]
d – pipe diameter, [m]
dr – flat circular absorber diameter, [m]
f – focal length, [m]
$f_{\text{theoretical}}$ – theoretical focal length, [m]
G_o – direct normal irradiance, [Wm^{-2}]
n – number of emitted rays
p_o – spiral coil pitch, [mm]
R – radius, [m]
$R_{\max}$ – maximum radius of the coil, [mm]
$R_{\min}$ – minimum radius of the coil, [mm]
R_1 – radius of parabolic dish reflector, [m]
R_2 – radius of centered hole, [m]
t – spiral parameter, [–]
x – x Cartesian co-ordinate, [m]
y – y Cartesian co-ordinate, [m]
z – polar co-ordinate, [m]

Greek symbols

δ – pipe wall thickness, [mm]
θ – polar angle, [rad]
ψ_{rim} – rim angle, [°]
ψ_1 – inner rim angle, [°]
ψ_2 – outer rim angle, [°]

Subscripts and superscripts

i – inside
o – outside
sun – Sun

Abbreviations

CPC – compound parabolic collector
CSP – concentrated solar power
DHI – diffuse hemispherical irradiance, [Wm^{-2}]
DI – diffuse irradiance, [Wm^{-2}]
DNI – direct normal insolation, [Wm^{-2}]
ETC – evacuated tube collector
FPC – flat plate collector
GHI – global hemispherical irradiance, [Wm^{-2}]
GI – global irradiation, [Wm^{-2}]
PMMA – polymethyl methacrylate
PTC – parabolic trough collector

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