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OPTICAL MODEL AND NUMERICAL SIMULATION OF THE NEW OFFSET TYPE PARABOLIC CONCENTRATOR WITH TWO TYPES OF SOLAR RECEIVERS

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Abstract. *The paper presents a physical and mathematical model of the new offset type parabolic concentrator and a numerical procedure for predicting its optical performances. Also presented is the process of design and optical ray tracing analysis of a low cost solar concentrator for medium temperature applications. This study develops and applies a new mathematical model for estimating the intercept factor of the solar concentrator based on its geometrical and optical behavior. The solar concentrating system consists of three offset parabolic dish reflectors and a solar thermal absorber at the focus. Two types of absorbers are discussed. One is a flat plate circular absorber and the other a spiral smooth pipe absorber. The simulation results could serve as a useful reference for design and optimization of offset parabolic concentrators.*

Key Words: *Optical Modeling, Parabolic Offset Reflector, Solar Energy, Ray Tracing Methodology, Geometric Factors, Characteristics of Concentration.*

1. INTRODUCTION

Solar energy is one of the alternative sources that can meet energy demands. This form of energy can be harnessed at a comparatively low cost. The device which is used to transform solar into heat energy is referred to as a solar thermal collector or STC. Depending on the temperatures gained by them, STCs can be divided into low, middle and high temperature systems. Mid-temperature systems are applicable for refrigeration systems and industrial processes. Among several types of solar concentrators, the multi-dish concentrator consisting of several discrete small dishes arouses wide interest. They

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are convenient for manufacturing, installation and mending discrete dishes. To avoid design complexity of a specific shaped surface solar concentrator, a common offset parabolic antenna is used to make the solar reflector. These types of antennas are widely used both in developed and underdeveloped countries and they are cheap and easy to obtain. A configuration with several offset parabolic antennas offers many advantages over most common centered-focus solar parabolic concentrators (focal point concentrators), like lower wind resistance and higher stability of the structure because of a lower center of gravity.

Munir [1] presented an experimental study of transforming solar energy into thermal energy by using a parabolic solar concentrator with a system of continual tracking of the sun. The experiment was carried out on a prototype of concentrator of 1 m in diameter and a copper receiver, 10 cm in diameter and 20 cm length. The receiver was located at the focal plane of the parabola. This model of parabolic solar concentrator led to the levels of temperatures ranging between 200⁰C and 350⁰C.

Bellel [2] studied the difference in performance of two types of solar cylindrical receivers. Bellel dealt particularly with problems of heat transfer in the absorber. In fact, the concentration of solar energy, which the absorber converts into thermal energy, allows one to meet various needs: hot water for different uses, production of electricity through the generation of steam, sterilization of objects (medical devices). Bhirud and Tandale [3] and Delaney [4] developed concentrators that are capable of delivering temperatures in the range of 300⁰C and are technically suitable for medium temperature applications. With a higher concentration ratio, there is an increase in temperature at which heat is delivered. It is observed from the comparison that the two axes tracking paraboloidal dish, which always faces the sun, is the most promising design for the concentrating systems justifying the use of the Scheffler concentrator for industrial process heat applications. These concentrators also provide an automatic tracking system. Scheffler [5] has shown that about half of the power of sunlight which is collected by the reflector becomes finally available in the cooking vessel. The use of solar energy for the generation of steam is now an economically attractive possibility since the payback period of such a system lies between 1.5 and 2 years. Ruelas et al. [6] developed and applied a new mathematical model for estimating the intercept factor of a Scheffler-type solar concentrator (STSC) based on the geometric and optical behavior of the concentrator in Cartesian coordinates. Reinalter et al. [7] investigated thermal and geometric features of the 10 kW receiver CNRS-PROMES system (parabolic reflector with diameter 3.8m, focal length 4.5m). The validation process of the thermal model was performed by comparing the experimental results reported for the 10 kW cavity receiver CNRS-PROMES system to the results obtained from the simulation of incoming solar radiation in laboratory conditions by using a solar simulator. Munir et al. [8] showed the design principle and calculation of a Scheffler fixed focus concentrator with the surface area of 8 m² for medium temperature applications. The authors proved mathematically that it is possible to construct a concentrator that can provide a fixed focus for each day in a year. Bugarin [9] presented the process of design and construction of a low-cost solar concentrator for cooking. This type of solar cooker produces vertically reflected rays that reach the food pot at the bottom like in conventional stoves. Rapp and Schwartz [10] constructed and successfully tested a 2m² parabolic dish solar concentrator (Scheffler Concentrator) to focus sunlight onto a stationary target. They described some ideas about the intricate design of the Scheffler reflectors and how they are developed. The parabolic Scheffler reflectors can provide for a high temperature heat for all types of cooking, steam generation and many

other applications. Macosko et al. [11] described a solar concentrator system designed to supply both thermal and electrical energy to a hydrogen reduction reactor modeled after the NASA Roxygen first generation system. A concept is defined that utilizes an offset parabolic concentrator to collect and focus solar energy directly into the Roxygen reactor. The offset parabolic concentrator was rotated to track the sun. A two axis solar tracking system and a concentrator positioning system were utilized to keep the concentrator perfectly aligned with the sun and the focal point centered at the reactor (receiver) aperture. Asmelash et al. [12] also designed and manufactured an offset type of solar concentrating system for cooking purposes. The concentrating offset collector had major and minor diameters of 90 by 80 cm respectively. The system was tested for its thermal performance following standard testing procedures of the American Society of Agricultural Engineers (ASAE) and it was found useful with an encouraging results. Maximum temperature of 940⁰C was achieved in the cooking vessel after 25 minutes. Patil et al. [13] investigated convection heat loss that inevitably occurs in receivers with high concentrating solar concentrators. They presented an experimental investigation of natural convection heat loss from the hemispherical cavity receiver with diameter 540 mm. The aim of the project was to develop the setup that may be used to identify the total heat loss and convective heat loss from the receiver. Cabanillas and Kopp [14] developed a solar parabolic dish concentrator with a diameter of 2.44 m and focal length of 0.92 m. They studied a solar spiral heat exchanger made from carbon steel in order to measure the energy efficiency and net energy gain of the concentration system. Saravanan et al. [15] designed solar biomass hybrid dryer for the purpose of drying 40 kg of cashew nut per batch. They have investigated the thermal performance of a solar biomass dryer. Their system consists of a solar flat plate collector, a biomass heater, a drying unit, a blower and a chimney. The solar air heating collector system consists of an absorber, a double glass cover, a back plate and insulation.

The offset parabolic reflectors are more efficient since objects placed at the focus do not create shadows over the reflecting surface. This paper also describes a prototype of an offset parabolic dish with 2400 mm in diameter. The system consists of three identical offset satellite dishes that are positioned in such a way that they concentrate sun radiation in the integral focal area with the desired area and geometry. This study develops and applies a new mathematical model for estimating the intercept factor of the solar concentrator based on its geometrical and optical behavior. This paper, however, does not devote much attention to experimental measurement and testing of thermal performance of the concentrating solar collectors. As a next step in the research, the experimental verification of simulated results is planned.

2. DESCRIPTION OF THE LOW-COST PARABOLIC OFFSET CONCENTRATING COLLECTOR FOR THERMAL APPLICATION

Fig. 1 shows a parabolic offset solar concentrator system installed in the Laboratory for Thermal Engineering at the Faculty of Mechanical Engineering, University of Niš. The system consists of three identical offset satellite dishes that are positioned in such a way that they concentrate sun radiation in the integral focal area. The inner surface of the offset parabolic dishes that faces the sun is covered with aluminum foil. The reflectivity of the foil ranges from 58 to 60%. The reflective foil should be cut in such a way that there are no wrinkles when they are glued to the surface of the dish; hence 10 cm wide rectangular

pieces are the optimum cut size for the offset parabolic dish. The concentration of solar radiation in a spiral absorber – receiver (focus surface area) is shown in Fig. 2.

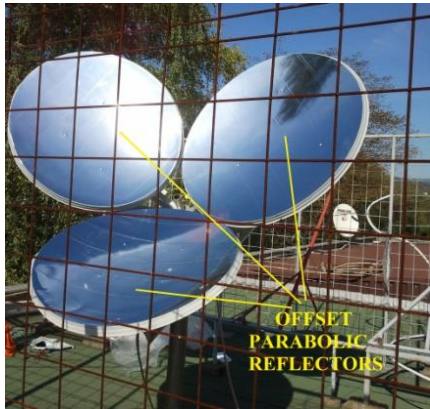


Fig. 1 Experimental model of a parabolic offset solar concentrator system



Fig. 2 Concentration of solar radiation at the spiral absorber pipe

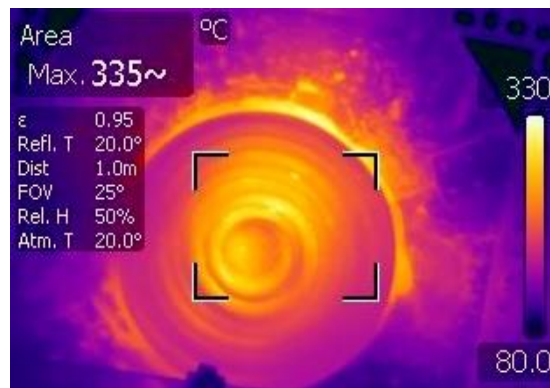


Fig. 3 Infrared image of the coil receiver taken at 15:05 pm on September, 30, 2014

Fig. 3 shows an infrared image of the coil receiver. The maximum measured surface temperature was 335° C. The day was clear and sunny. The measurement was performed with the thermal imaging camera FLIR E30. It was expected that the temperature at the coil receiver would be about 400° C in July or August.

2.1. Physical model of the offset type parabolic dish concentrator with a thermal spiral tube absorber

The offset solar parabolic concentrator is the result of the interception of the open circular area with a small side section of the parabola. It directs solar radiation to a fixed focus point where a solar absorber - receiver is installed and secured by a fixed support structure.

It was made from low carbon manganese steel. The support structure of the offset solar parabolic dish concentrator was made by welding a large number of metal profiles with a square cross-section ($0.03 \times 0.03\text{m}$). Parabolic offset reflectors were placed on the support structure by using adequate trusses which enabled the reflectors to be dismantled from the support structure at any given moment. Adjustment of the elevation angle of each of three offset reflectors is possible in the range from 0° to 30° relative to the horizontal plane of the support structure.

The mechanical structure should allow the positioning of the three parabolic offset reflectors into the optimal position in which solar rays strike the solar concentrator at angle of 90° . The authors performed several numerical simulations of dynamic loads for various wind speeds and angle of attack. The system was designed in the following way. The reflectors track the sun up to the wind speed of $v_w = 20\text{m/s}$. At greater speeds, the system stops tracking the sun and gets itself into the most stable position which is the horizontal one. The system was designed with the applied CAD technologies and calculated to withstand the maximal wind speed of $v_{wmax} = 25\text{m/s}$ (Finite Element Method). Figs. 4a and 4b show the solar concentrating system in the working and safety positions.

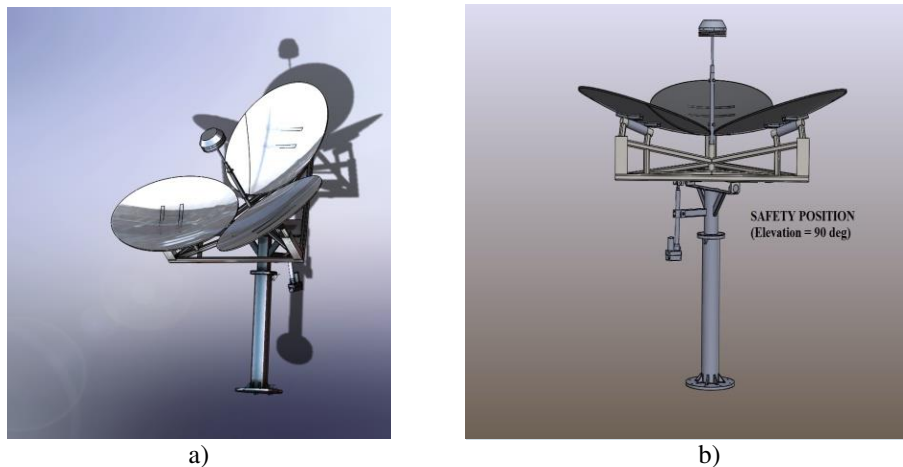


Fig. 4 a) Working position of the offset parabolic dish solar concentrator (axonometric view);
b) safety position (elevation angle of 90°)

The main elements of the offset parabolic dish concentrator system in the working position are shown in Fig. 4a. One of the essential elements of the solar system is the possibility of a permanent tracking position of the sun (azimuth and elevation). The incident angle of sun rays is parallel to the optical axis of the solar concentrating system. The system remains in the safety position during the night, only to take up the working position after sunrise (tracking mode).

2.2. Mathematical modeling of the solar offset parabolic concentrator

Design parameters of the solar offset parabolic concentrator are illustrated in Table 1 [16]. Mathematical modeling (calculation) for the whole geometric model of the offset

parabolic concentrator was done in Wolfram Mathematica v.8.0. The numerical solution of the mathematical model was used to obtain geometric parameters such as the radius of the smaller and larger semi axis of the ellipse, the focal length, and the tangent slope for the three offset reflectors. Parameters obtained from mathematical analysis were used as input parameters for 3D modeling in the CAD program CATIA V5R19 - Dassault Systems, USA. The first step was to design a rotational paraboloid with diameter $D = 5000$ mm and focal length $f = 1600$ mm. The next step was to design a circular cylinder with diameter $D = 1100$ mm, which was positioned parallel to the optical axis of the rotational paraboloid at the distance of 100 mm from the optical axis. The three cylinders were positioned parallel to the optical axis and the angle between the axes of the cylinders was 120° . Unlike a conventional paraboloid concentrator, the offset parabolic concentrator system fixed focus concentrator is a lateral part of a paraboloid as shown in Fig. 5a. Fig. 6 shows the structure and geometric model of the new type of solar offset parabolic concentrator. The choice of the optimal position of the solar thermal absorber – receiver was carried out on the basis of Monte Carlo ray tracing analysis model of the offset type parabolic concentrator dish and receiver. The optimal focal distance is 1155 mm, while the theoretical focal distance is 1600 mm - focal hot spot.

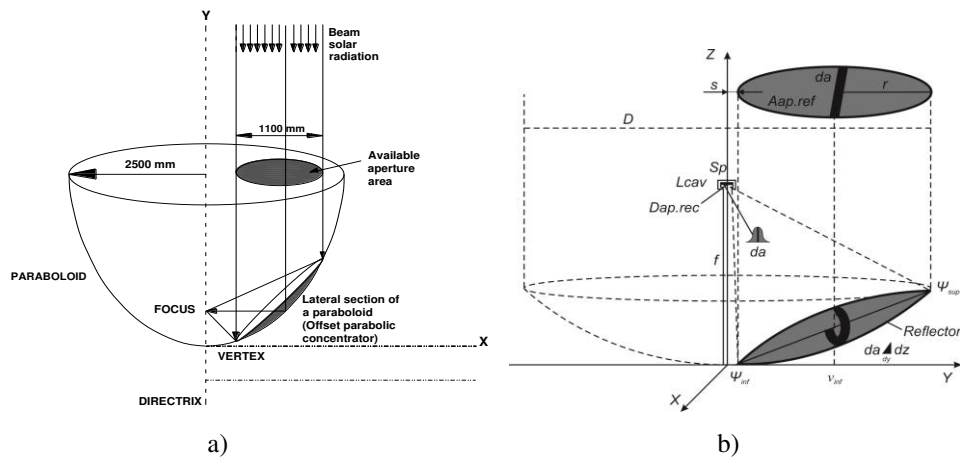


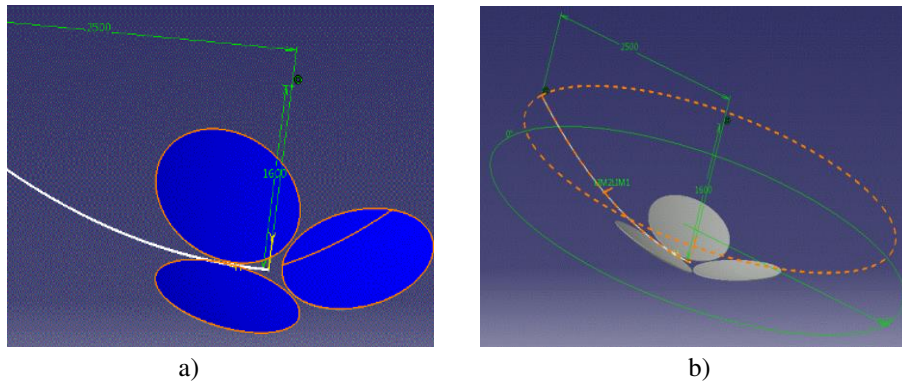
Fig. 5 a) Section of the offset parabolic solar dish concentrator from baseline paraboloid;
b) Process of determining an offset parabolic solar dish concentrator

The mathematical representation of the parabolic concentrator is paraboloid which can be represented as a surface obtained by rotating the parabola around the axis. Mathematical equations for the parabolic dish solar concentrator in Cartesian coordinate systems are defined as:

$$x^2 + y^2 = 4fz \quad (1)$$

Table 1 Geometric parameters of the offset parabolic dish concentrator, Pavlovic et al. [16]

Design parameter	Numerical value	Unit
Major diameter of reflector D_{ref}	1.20	[m]
Minor diameter of reflector D_{ref}	1.10	[m]
Cross-section of opening offset parabolic concentrator A_{proj}	5.31	[m ²]
Sheltered area of concentrator A_{shadow}	0	[m ²]
Effective area of offset concentrator $A_{ap,ref}$	2.85	[m ²]
Receiver diameter	0.20	[m]
Diameter of baseline paraboloid	5	[m]
Depth of baseline paraboloid	0.98	[m]
Depth of offset parabolic concentrator	0.33	[m]
Focal length	1.6	[m]
ψ_1 - rim angle	43.15	[⁰]
Absorber area	0.0314	[m ²]
Geometric concentration ratio $CR_g = A_{ap}/A_{rec}$	96.01	[-]
Optical (flux) concentration ratio $CR_0 = I_{rec}/I_{ap} = I_{rec}/DNI$	87,07	[-]
Surface reflectance ρ	0.60	[-]
Direct solar radiation I_d	800	W/m ²

**Fig. 6** a) Structure of the new type of solar offset parabolic concentrator;
b) Geometrical model of the new type of solar offset parabolic concentrator

Usually the paraboloids that are used in solar collectors have rim angles from 10 to 90 degrees. The relationship between the relative aperture and the rim angle is given by:

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

Intercept factor φ represents the fraction of the radiation intercepted by the cavity receiver and is calculated by Eq. (3) with a change over the term of the fraction of the captured flux, using $\Gamma^{1.975}$ instead of Γ .

The shadow produced by the receiver was considered as a dead area on the projected area of dish reflective surface A_{dish} . Power consumption for the tracking and controlling systems were neglected.

$$\varphi = \frac{\sum_{\psi=0}^{\psi} \Gamma^{1.975} 8\pi I_f \sin(\psi) \Delta\psi}{IA_{dish}} \quad (3)$$

The incident energy received by solar spiral absorber of offset parabolic dish concentrator can be computed from the following equation:

$$Q_s = I_b \rho(\tau\alpha)_e \gamma C \quad (4)$$

The optical efficiency of that solar concentrator can be computed from:

$$\eta_0 = \rho_c(\tau\alpha)_e \gamma \quad (5)$$

3. PHYSICAL MODELS OF TWO TYPES OF SOLAR SPIRAL THERMAL RECEIVERS

In terms of their configuration, receivers can be flat receivers or cavity receivers. The first ones focal absorber surfaces, whilst the latter ones have the absorber surface surrounded by an insulated cover, with a sufficient opening to capture the radiation from the concentrator. The shape of the receiver depends on its dimension and the concentrator focal length/rim angle. Photo thermal conversion in a dish cavity receiver is a key process to efficiently utilize solar energy, mainly because the cavity receiver converts the collected solar radiation into thermal energy by coupling the complicated heat transfer.

This paper analyzes two types of solar thermal receivers presented in Fig. 7. The first type is the solar thermal receiver with a flat plate. The receiver is a metal disc painted black. The second type is the Archimedean spiral smooth pipe directly exposed to reflected radiation from the offset dish concentrator.

The receptor portion of the heat exchanger has three primary components, all made of stainless steel. The spiral pipe absorber creates a spiral path for fluid to flow through.

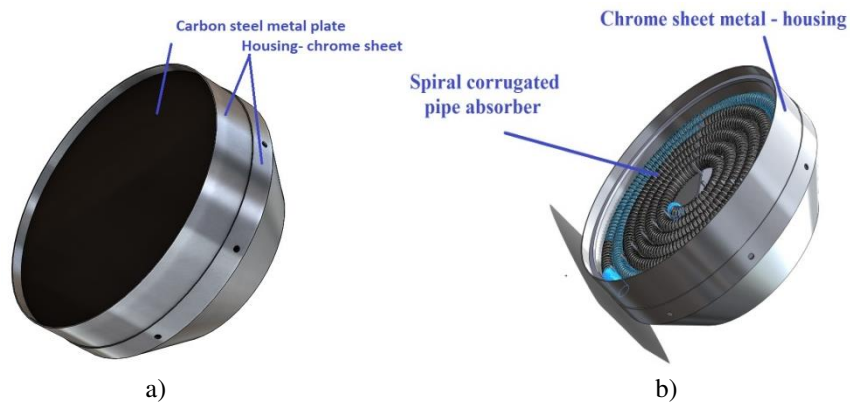


Fig. 7 Two types of solar thermal receivers: a) flat plate painted black; b) spiral pipe

The flow rates in spiral absorber pipe are changeable data. The next step is to create an experimental installation in the Mechanical Engineering Laboratory for testing and thermal hydraulic performance of said heat exchangers in stationary conditions. The

installations will be able simulations of real solar modules (offset parabolic concentrator). They will serve as the basis for investigating the work of the spiral absorber at different geometric and spatial configurations, fluid flow, heat input levels, as well as the fluids with significantly different thermo-physical properties (water and a solution of propylene glycol). In order to assess the efficiency of the heat exchanger the measurement of thermal and hydraulic losses will be carried out.

The spiral smooth pipe absorber is directly exposed to reflected radiation from the dish concentrator. Solar energy systems can improve effectiveness of their receivers by covering them with a selective absorber coating. The spiral pipe receiver is made of stainless steel AISI 304 with a coil of 10 mm in outer diameter and 8 mm in inner diameter rolled into a spiral shape of 200 mm in diameter. The length of spiral pipe absorber is about 2.5 m. Usually in this type of receiver the liquid circulates inside the tube, entering from the rim and leaving at the center where the radiation intensity and temperature are higher (Fig. 8a and 8b). To avoid pipe deformations, the receiver has a small hole in the center, of about 40 mm in diameter. The incidence angle of the offset parabolic concentrator is zero $\theta_i = 0$.

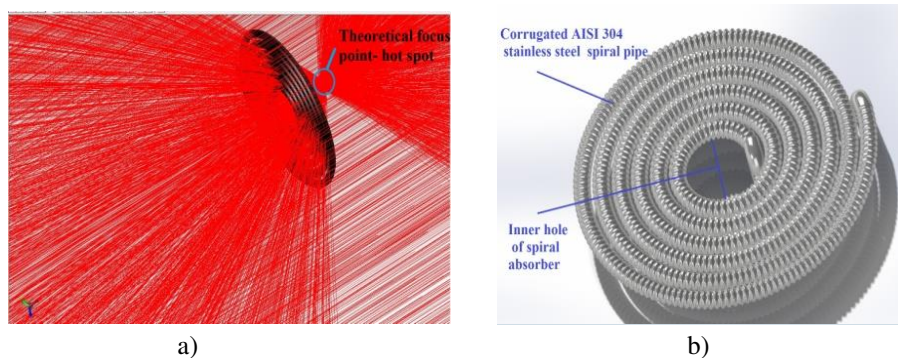


Fig. 8 a) Trace of concentrated rays at the spiral absorber pipe; b) spiral flat coil absorber

Both types of receivers are painted black on the side facing the concentrator so that they would be able to absorb the maximum amount of thermal energy. The test plate – a metal circular disk, is used to determine where the focal area of the concentrator is. In other words, it is used to determine where the receiver should be placed in relation to the concentrator.

4. RESULTS AND DISCUSSION

4.1. Optical analysis of the offset parabolic concentrator

The optical analysis of the offset parabolic concentrator was carried out in the commercial software TracePro ver. 7.4.2, Lambda Research Corporation, USA. Two types of absorbers were analyzed: the flat plate circular absorber and the spiral smooth pipe absorber.

4.1.1. Optical analysis of the offset parabolic concentrator with a flat plate circular type of absorber

In TracePro the three offset parabolic reflectors were defined as a surface with reflective coating. The reflectance coefficient was 60%. The receiver was a flat plate circular absorber

with the diameter of 200 mm and 5 mm in thickness. The absorbing surface was defined as the perfect absorber ($\alpha = 1$). The position of the receiver was found by calculating the optimal flux for the given receiver. The optimal position was found at 1155 mm from the vertex of the parabolic dish, after several calculations in TracePro. At a distance of 1155 mm the best value of total flux was obtained - solar power and irradiance flux density distribution. After defining the geometry of the offset parabolic solar concentrator, the radiation source was defined. The radiation source was circular with the same diameter as that of the parabolic dish (2400 mm). The radiation source was placed 1500 mm from the vertex of the offset solar parabolic concentrator and had a circular grid pattern for the Monte Carlo ray tracing. The spatial profile of generated rays was uniform and the angular profile was solar radiation. The input parameter for the optical analysis was the solar irradiance which was set to 800 W/m^2 . Experimental values for solar irradiation for the City of Niš in Serbia are between 750 W/m^2 and 900 W/m^2 . The optical system for the offset parabolic solar concentrator with traced rays is given in Fig. 9. Since the offset parabolic concentrator continually tracked the sun, the incidence angle of solar rays was always $\theta = 0^\circ$. For this type of solar concentrator cosine losses do not exist.

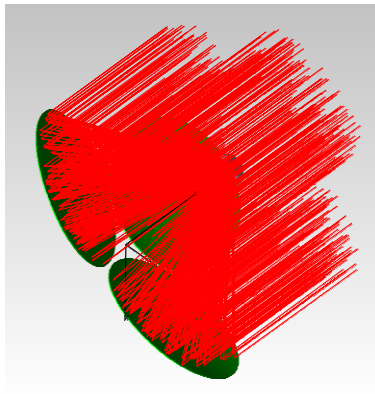


Fig. 9 Ray tracing model of the offset parabolic solar concentrator with the flat plate circular absorber

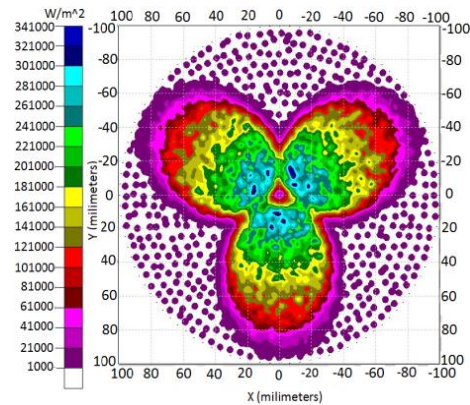


Fig. 10 Solar flux distribution on the absorber surface

The optical analysis was done by generating 119401 rays and calculating them by the Monte Carlo ray trace. From all the emitted rays only 76058 rays reached the absorber surface, which was 64% of the emitted rays. The calculated irradiance for the absorbed rays on the receiver was from $3.88 \cdot 10^{-9} \text{ W/m}^2$ to $3.25 \cdot 10^5 \text{ W/m}^2$. The total calculated flux on the flat plate receiver was 2188 W. Fig. 10 shows the total irradiance map for the absorbed flux on the receiver.

4.1.2. Optical analysis of the offset parabolic concentrator with a spiral smooth pipe absorber

The second optical analysis was performed on the more complicated model of the solar absorber. The solar absorber was the spiral pipe absorber described in the previous section. The position of the receiver was found by calculating the optimal flux for the

given receiver. The optimal position of the receiver was 1155 mm from the vertex of the parabolic dish.

The optical analysis for the system with the smooth pipe absorber was done by calculating two sets of rays. The first set contained 119401 rays and the second set contained 1078201 rays. All rays were calculated by the Monte Carlo ray trace. For the first set of rays, from 119401 emitted rays only 49886 rays reached the absorber surface which was 42% of rays. The average irradiance – the local flux density was 57859 W/m^2 . The calculated irradiance for the absorbed rays on the receiver was from $1.625 \cdot 10^{-15} \text{ W/m}^2$ to $4.124 \cdot 10^5 \text{ W/m}^2$. The total calculated solar flux on the spiral pipe receiver was 1435.4 W. The total irradiance map for the absorbed flux on the receiver for the first set of rays is shown in Fig. 11.

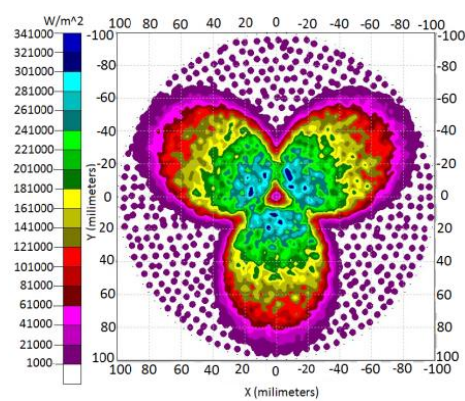


Fig. 11 Solar flux distribution on the absorber surface - 119 401 simulated rays

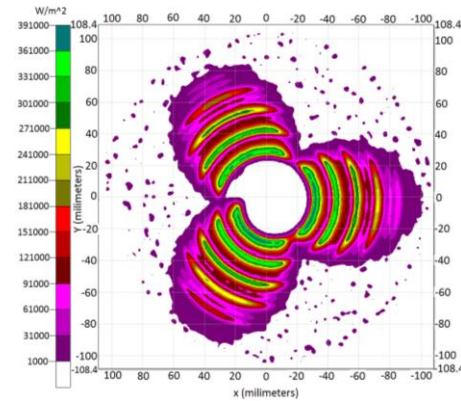


Fig. 12 Solar flux distribution on the absorber surface - 1078201 simulated rays

For the second set of rays, from 1078201 emitted rays only 515418 rays reached the absorber surface which was 48% of rays. The average irradiance – the local flux density was 66195 W/m^2 . The calculated irradiance for the absorbed rays on the receiver was from $1.2207 \cdot 10^{-15} \text{ W/m}^2$ to $3.8733 \cdot 10^5 \text{ W/m}^2$. The total calculated solar flux on the spiral pipe receiver was 1642.3 W. The total irradiance map for the absorbed flux on the receiver for the second set of rays is shown in Fig. 12.

From the presented data for the first and second set of rays it can be concluded that it is very important to properly define a set of rays. For a simple solar absorber, such as a plate circular disc, a set of 119401 rays is more than enough, but for a complex type of the solar absorber, such as a spiral smooth pipe absorber, one ought to define much more rays to get valid results.

5. CONCLUSION

The authors have developed a completely new model of the offset parabolic dish concentrator. The presented simulation results could serve as a useful reference for the design and optimization of offset parabolic concentrators. As a next step in the research, the experimental verification of simulated results is planned. The authors intend to improve the

design of the absorber by developing a solar receiver with a cavity. This type of receiver has significantly smaller convective and radiation losses and greater conversion efficiency of solar radiation to heat.

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