Dear Sir,

Please receive the revised paper (for archival publication) titled “Efficiency of solar ray use by parabolic, cylindrical solar concentrator for heat production” by Milorad Bojić, Nenad Marjanović, Ivan Miletić to be presented at 5th DUBROVNIK CONFERENCE ON SUSTAINABLE DEVELOPMENT OF ENERGY WATER AND ENVIRONMENT SYSTEMS. The paper keywords are the following: solar energy, concentrator, heat, CATIA, software.

Kragujevac, 28. July 2009.

Best regards

Milorad Bojic

Prof. Milorad Bojic
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Response to Reviewer's comments:
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Comment (a) The explanation of Î´, the aperture angle of the concentrator, as given in Fig. 2 is misleading, since any other parallel ray would give different intersection with the O - F line, and thus, different Î´ value. In my opinion, the real width of the aperture area is the linear section between points T and F, and the real aperture angle can be defined as the angle between lines OF and TF. (Though this angle is much larger, in this case also all rays of the beam radiation that are not absorbed by the reflecting surface have the chance to collide with or to be reflected to the adsorber.)
Response: I agree with the reviewer that the angle (delta) is misleading compared to the location of the light ray, however (delta) does not have to do anything with the light ray. (Delta) is simply angle between the tangent line on the parabola at the parabola rim T and line TF representing the aperture width of the concentrator.
Comment: (b) Fig. 7 also is not correct: Here &quot;Eficasnost&quot; certainly means Efficiency. Since efficiency is, per definition (Cf., Equ. (2), the sum of curves 0, 1, 2, 3 and 3+, in that hypothetical case when the reflectivity is near 100 %, the efficiency also should be also near 100 %. Even in that extreme case, when the reflectivity is zero % (all rays colliding the reflector are immediately absorbed) up to about 40 degrees altitude angle, curve 0 (that refers to zero reflection)itself is much higher than the efficiency line given in Fig. 7.
Response: Fig.7 was not correct as “Efikasnost” should not be written there at all. “efikasnost” is erased from this figure.
Therefore, I propose to redraw Figs. 2 and 7, and rewrite their interpretation.
Further revisions: Figures 1-7 are revised for better comprehension and some other explanation added.

Editor's comments:
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Please also include a modeling and numerical error analysis.
Response. The analysis is included in separate part of the paper devoted to the error analysis. The errors are presented by two separate figures.

# Efficiency of solar ray use by parabolic, cylindrical solar concentrator for heat production

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## ABSTRACT

Long stationary parabolic, cylindrical solar concentrator for heat production consists of the aluminium absorber (with water pipes inside) and parabolic, cylindrical reflector (with metal surface) and has geometrical concentration ratio up to 4. it is of CP-180A type. Direct solar radiation approaches the concentrator aperture at different angles and pathways. For different aperture angles and different kinds and types of metal surfaces of the reflector, it would be investigated how efficiently the direct solar radiation reaches absorber to be converted to heat by using software CATIA.

## INTRODUCTION

Temperature increase has been constantly recorded on the global level. The increase is due to green-house effect because of CO2 emission from different sources in atmosphere. Usually this emission is blamed to combustion of fossil fuels mainly for heating and electricity production. A response to such a situation of world community may be increased use of solar energy for heating, cooling, and electricity production. Solar energy is source of all life on the earth and it is in abundance but dispersed. Here, we propose use of stationary, asymmetric solar concentrator for conversion of solar energy for heat production.

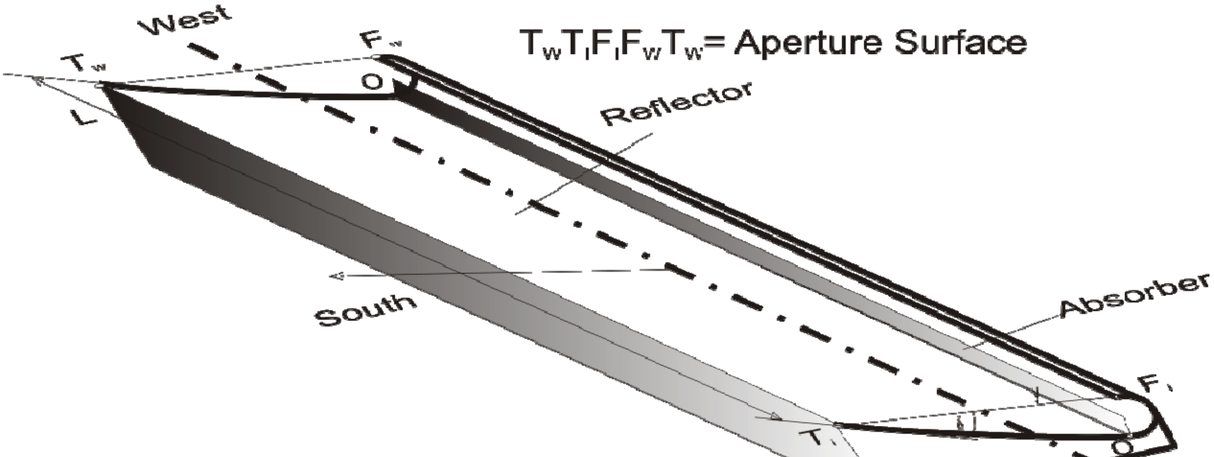

Fig. 1. The concentrator. The concentrator is positioned to have the reflector trough in the direction east-west, while the reflector surface faces south (valid for the north hemisphere)

The subject of this research (in Centre of heating, air conditioning and solar energy of Mechanical Engineering Faculty at Kragujevac in Kragujevac University in Serbia) is design optimization of stationary asymmetric solar concentrator (type CP-180A) for heat production with geometric concentration of up to 4 (see Fig.1 and 2).

The stationary (long) solar concentrators have advantages over tracking concentrators as they can be part of building façade and used in building and city architecture.

The conventional solar panels only use half of their available surface area. The bottom half of the panel faces downward. The panel is easily may accept more Solar energy than is incident on the top surface of a conventional panel. Here, illumination of both sides of the panel is performed with non-imaging reflectors. This allows a single absorber to be used instead of the two standard single-sided absorbers. This may represents a substantial cost and materials saving.

Such a design approach has a number of implications: (a) The panel must be substantially thicker because of the necessity for reflective optics to reside underneath. This can be an aesthetic issue. (b) The heat loss mechanism underneath the panel is different to that of the top surface. (c) Additional reflector material must be used. Its cost and pollution must be compared to that of the replaced panel.

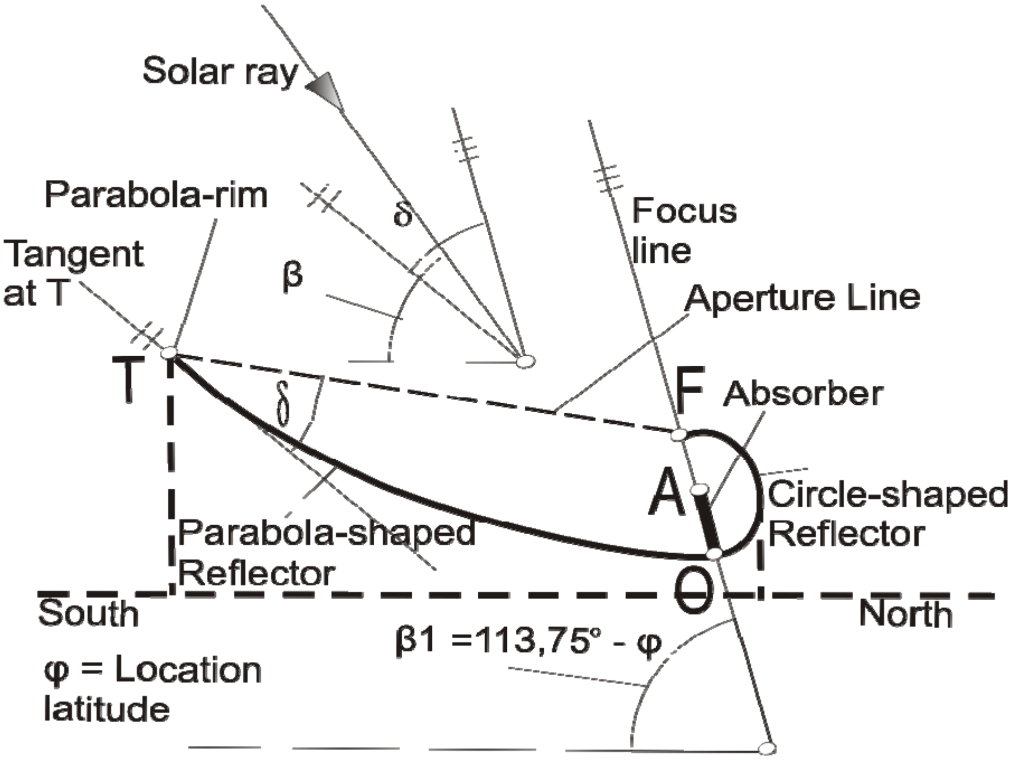

Figure 2. Schematic of vertcal cut throuh the concentrator in the plane perpendicular to the direction east west.

This type of concentrators was already subject of intensive research [1-5]. This paper investigates the pathways of the direct solar radiation through the concentrator aperture and inside the concentrator by using computer software CATIA. In addition the paper would present results of efficiency of use of direct solar rays at concentrator for different types of reflector surface. These investigations are performed for different angles of incident of solar rays.

## CONCENTRATOR DESIGN

### Design description

A stationary asymmetric solar concentrator shown in Fig.1 consists of a reflector and absorber. The reflector has partially parabolic and partially cylindrical shape. The reflector is covered with different materials that have good reflectivity. The absorber has plate shape. This is basically aluminium covered with solar cells on its both sides. Inside the absorber, the heat transfer fluid flows through the copper pipes and takes excess heat out. The aperture of this solar concentrator is an imaginary surface $T_WT_IF_IF_WT_W$. Here line $T_WT_I$ presents the rim of the parabolic reflector and line $F_IF_W$ represents its focus line.

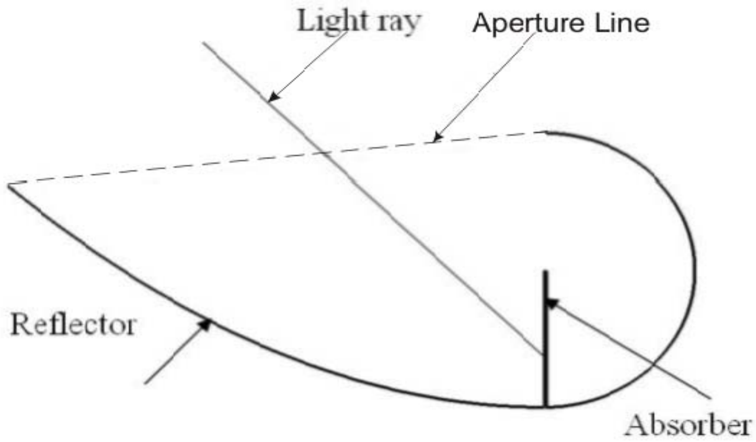

Figure 3. Light ray path toward the absorber of the concentretor that hits the absorber directly (the cross cut of parabolic-cylindric concentrator with one parabolic and cylindric reflector).

The vertical cut of the concentrator in Fig.1 is schematically shown in Fig.2. The concentrator consists of reflector (bold curve TOF) and absorber (bold line OA). The reflector consists of parabola part TO and circle part OF. Curve TO represents a part of parabola with its focus at F and vertex at O. Point T represents rim of reflector parabola for this concentrator. The line passing through points FO is called focus line of the reflector parabola. Curve OF represents a half of circle-shaped reflector with its centre at point A. The absorber width AO represents circle radius. The parabola focal distance OF is equal to the diameter of the circle shaped reflector.

The concentrator operates as the following. The direct solar radiation falls on the different parts of the reflector surface (Figs.3-6). The reflector surface reflects the solar radiation toward the absorber. All reflected solar radiation hits and concentrates to the absorber. In the absorber, the concentrated solar radiation is transformed into heat. The heat is collected by the heat transfer fluid and transferred away from the absorber.

### Concentrator position

The position of the concentrator is shown in Fig.1 and Fig.2. The concentrator is positioned to have the reflector trough in the direction east-west, while the reflector surface faces south (valid for the north hemisphere). Reflector trough is long enough to minimize loss of solar radiation for sun rays with solar azimuth different than zero.

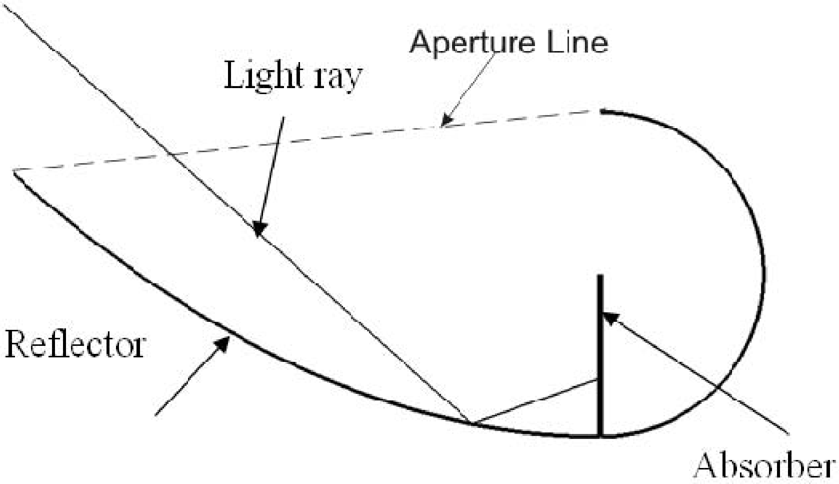

Figure 4. Light ray path toward the absorber of the concentretor with one reflection from reflector (the cross cut of parabolic-cylindric concentrator with one parabolic and cylindric reflector).

The vertical location angle $\beta_1$ of the concentrator facing south is the angle between the focus line of the reflector parabola and horizontal direction due south. This angle is calculated as

$$\beta_1=113.75^0-\varphi. \tag{1}$$

Here, $\varphi$ stands for the latitude of location ($\varphi = 44^0$ for Kragujevac, Serbia).

From Fig.2, the width of concentrator aperture area is line TF. The aperture angle $\delta$ is defined as an angle between a tangent on reflector parabola at rim point T and the aperture line TF. This angle is the same as the angle between a tangent on the reflector parabola at point T and the focus line of the reflector parabola.

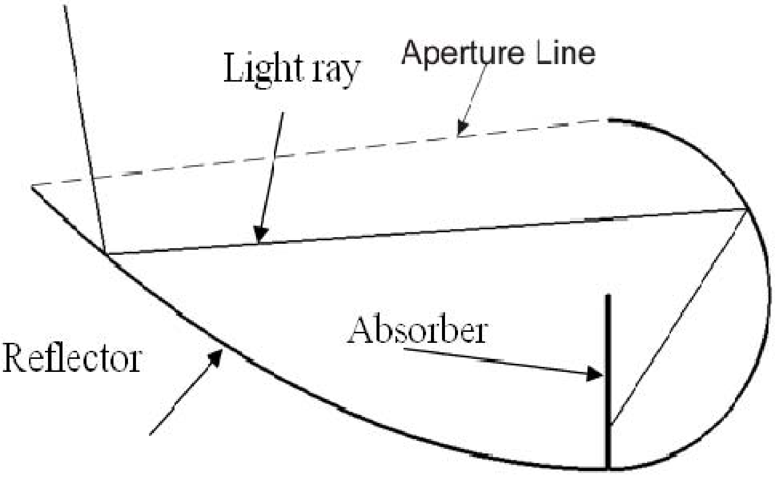

Fig. 5. Light ray path toward the absorber of the concentretor with two reflections from reflector (the cross cut of parabolic-cylindric concentrator with one parabolic and cylindric reflector).

The concentrator will not concentrate all sun rays that reach absorber through the concentrator aperture. It would concentrate the solar rays that have altitude value $\beta_1 - \delta < \beta < \beta_1$. This the reason why angle $\delta$ is called the aperture angle as it is also called in publications [1-3].

## Light Ray Paths

Fig. 3-6 shows the light ray paths toward the absorber of the concentrator obtained by computer software CATIA. In these figures, we show the travel path of several light rays. Basically, light rays may hit the absorber from the front side (Figs.3 and 4), from the back side (Figs.5 and 6), and may miss the absorber. In Fig.3, the light rays hit absorber directly. In Fig.4, the light rays hit absorber after single hit to the reflector. In Fig. 5, the light rays hit absorber after two hits to the reflector. In Fig. 6, the light rays hit absorber after 5 hits to the reflector.

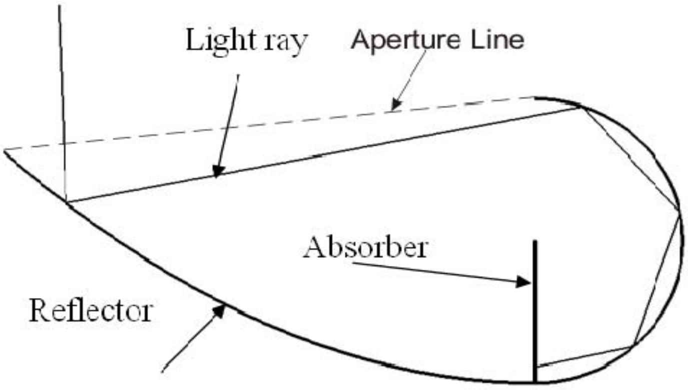

Fig. 6. Light ray path toward the absorber of the concentretor with 4 reflections (the cross cut of parabolic-cylindric concentrator with one parabolic and cylindric reflector).

For instance, if the aperture area is A, then $A_0$ stands for the part of A where the rays pass without any reflection from the reflector hitting directly the absorber. $A_1$ stands for the part of the aperture area through which solar rays pass that hit the reflector once before colliding with the absorber. $A_2$ stands for the part of the aperture area through which solar rays pass that hit the reflector two times before colliding with the absorber. $A_3$ stands for the part of the aperture area through which solar rays pass that hit the reflector three times before colliding with the absorber. $A_{>3}$ stands for the part of the aperture area through which solar rays pass that hit the reflector more than three times before colliding with the absorber. It holds that

$$A=A_0+ A_1+ A_2+ A_3+ A_{>3} \qquad (2)$$

We also define relative area vales of these surfaces in percents as

$$a_0=100A_0/A;\ a_1=100A_1/A;\ a_2=100A_2/A;\ a_3=100A_3/A;\ a_{>3}=100A_{>3}/A \qquad (3)$$

Here, it holds

$$a_0+ a_1+ a_2+ a_3+ a_{>3}=100. \qquad (4)$$

**Efficiency**

The efficiency of transfer of solar energy to concentrator absorber is given by the following expression

$$e= (A_0 +r A_1 + r^2 A_2 + r^3 A_3 +r^4 A_{>3})/A =a_0 +r a_1 + r^2 a_2 + r^3 a_3 +r^4 a_{>3}. \qquad (5)$$

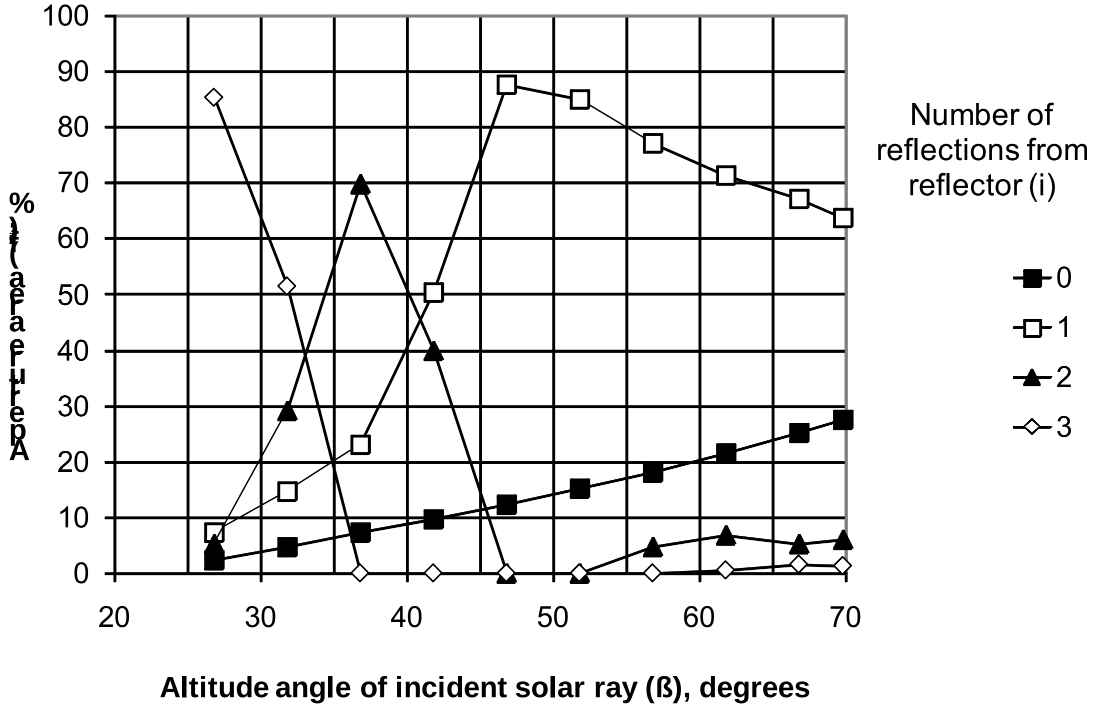

Fig. 7. Aperture area as a function of altitude angle of incident solar ray

## RESULTS AND DISCUSSION

### Number of Reflections

For the same altitude angle, the different types of solar rays would pass through different size of the aperture area. Fig. 7 shows values the aperture area entered by different types of solar rays (with zero, 1, 2, 3, and more than 3) as a function of the altitude angles of incident solar rays. The aperture area is given in percents of the total aperture area of concentrator. These curves are provided for different types of light rays that are incident on the aperture surface. Types of light rays depend on the way how they propagate inside the concentrator to reach the absorber surface. The investigated types were light rays that hit absorber surface without reflection from the reflector, with one reflection from the reflector, with two reflections from the reflector, with three reflections from the reflector, and with more than three reflections from the reflector. The altitude angles were varied from $21.75^0$ to $69.75^0$.

Regarding the type of light ray, the highest percentage of aperture is that of the light rays that hit absorber with one reflection from reflector for the incident angles from $40^0$ to $50^0$. For angles from around $50^0$ to $60^0$, the highest percentage of aperture is that of the light rays that hit absorber with two reflections from the reflector. For angles from around $60^0$ to $69.75^0$, the highest percentage of aperture is that of the light rays that hit absorber with three reflections from the reflector.

Table 1. Reflectivity coefficients for different materials of the reflector

| | *Material* | *Reflectivity Coefficients (r)* | *Relative numerical error, %* |
|---|---|---|---|
| 1 | Aluminium foil | 0.96 | 0.52 |
| 2 | Chrom polished | 0.92 | 0.54 |
| 3 | Iron polished | 0.86 | 0.58 |
| 4 | AL heavily oxidized | 0.80 | 0.62 |

**Efficiency of Concentrator**

Fig. 8 shows efficiency of reflectors to transfer light rays to the absorber at the concentrator as a function of altitude angles of incident of solar rays. These angles were varied from $21.75^0$ to $69.75^0$. These curves are provided for different types of reflector surfaces: Aluminium foil, polished chrome, polished iron, heavily oxidized aluminium. Their reflectivity coefficients are given in Table 1.

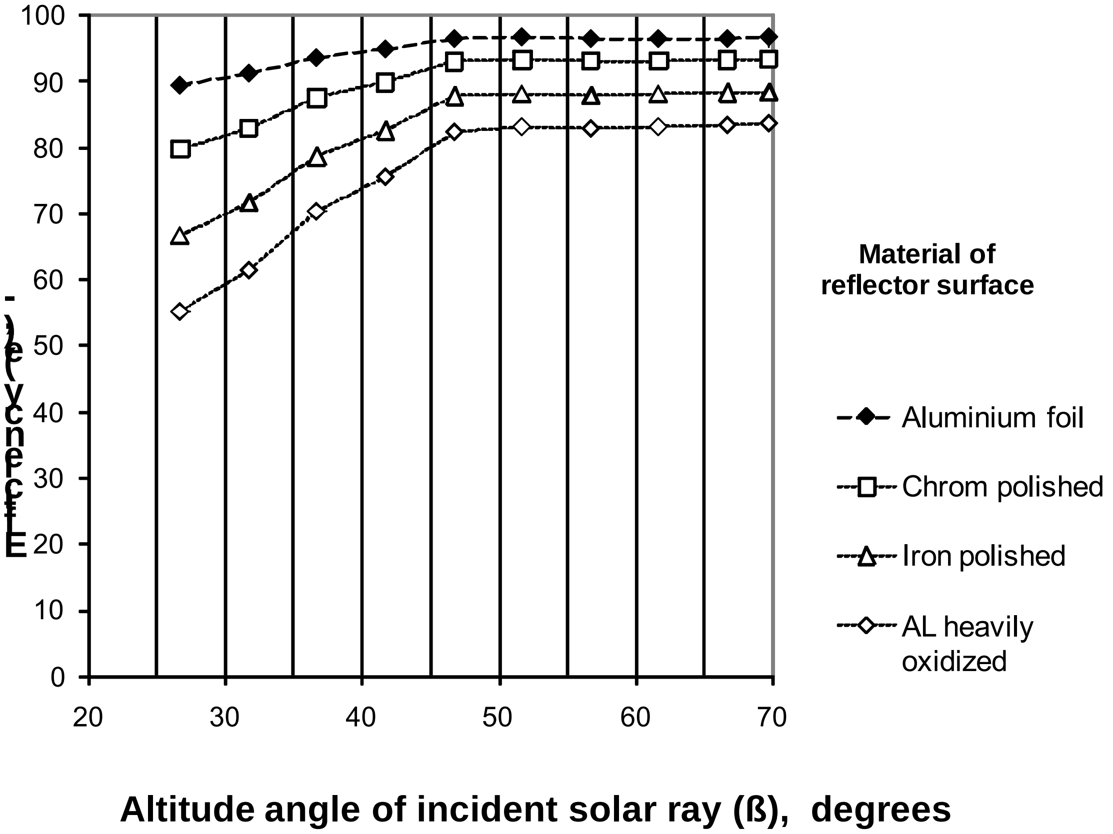

Fig. 8. Efficiency of reflectors as a function of the altitude angle of incident solar rays.

Regarding the type of reflector surface, the highest efficiency is that of the light rays that hit reflector with aluminium foil. Regarding the angle of solar ray incidence, the highest efficiency is that for angles from $21.75^0$ to $45^0$. When angle of altitude of solar ray goes up from 45 to 69.75, this efficiency decreases between 10-45% depending on the material of the reflector surface.

### Modelling and Numerical Error Analysis

For modelling of number of reflections, the geometry of parabola in software CATIA is given by analytical equation. Then, all points of geometry of sun rays are calculated by the software by using double precision. This means that values of the relative areas of aperture ($a_0$, $a_1$, $a_2$, $a_3$, and $a_{>3}$) are also calculated by double precision. In this case, there is no any significant numerical error. However, in Fig.7, the value for $a_{>3}$ was not reported, which introduces the modelling error in the range of 2%, which is relatively low. This error is present for the higher aptitude angles of incidence solar rays (see Fig. 9).

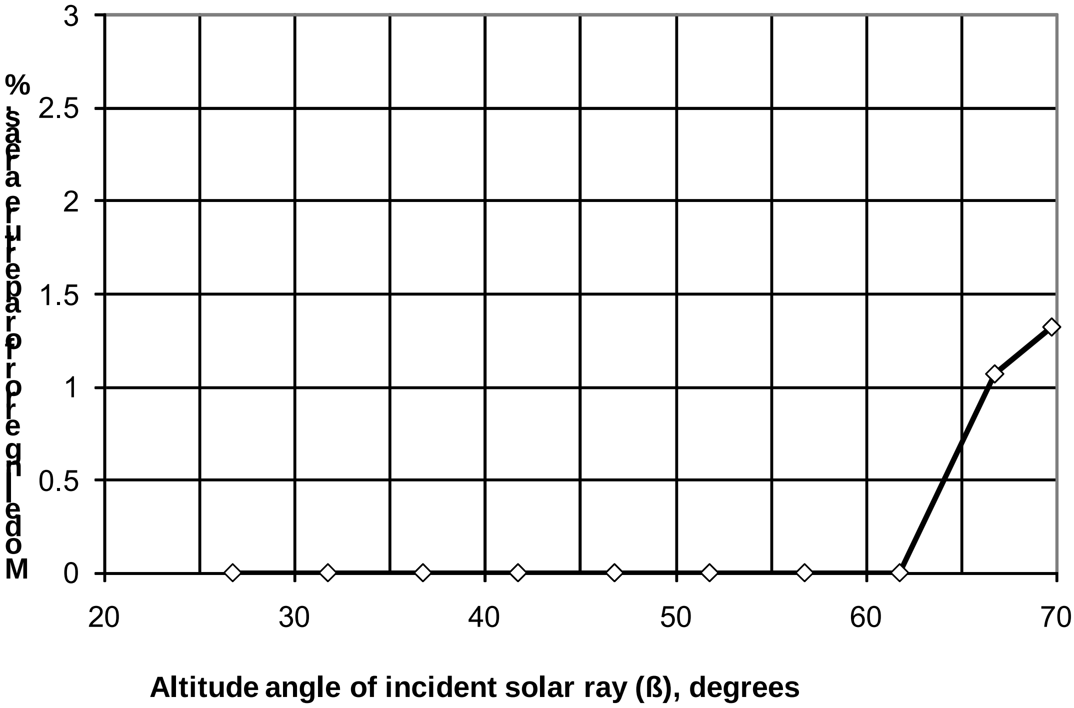

Fig.9 Modelling error for the aperture areas reported in Fig.7

For the case of calculating of efficiency of reflection of solar rays as a function of altitude angle of solar rays, the maximum absolute numerical error for efficiency is given as [6]:

$$\Delta e = \Delta a_0 + \Delta(r\, a_1) + \Delta(r^2\, a_2) + \Delta(r^3\, a_3) + \Delta(r^4\, a_{>3}). \qquad (6)$$

In this expression, $\Delta a_0 = a_0\,(S_{a0})$, $\Delta(r\, a_1) = r\, a_1\,(S_r + S_{a1})$, $\Delta(r^2\, a_2) = r^2\, a_2(2\, S_r + S_{a2})$, $\Delta(r^3\, a_3) = r^3\, a_3\,(3\, S_r + S_{a3})$, and $\Delta(r^4\, a_{>3}) = r^4\, a_{>3}(4\, S_r + S_{>3})$. Here, $S_r$ stands for the maximum numerical error of reflectivity coefficient, $S_{a0}$ stands for the maximum numerical error for $a_0$, $S_{a1}$ stands for the maximum numerical error for $a_1$, $S_{a2}$ stands for the maximum numerical error for $a_2$, $S_{a3}$ stands for the maximum numerical error for $a_3$, and $S_{a>3}$ stands for the maximum numerical error for $a_{>3}$. Finally, maximum relative numerical error for efficiency is given as

$$S_e = \Delta e/e. \qquad (7)$$

For different angles of incidence of solar rays, modest errors are obtained by using previous formula. The results are given on Fig. 10. These errors are in the range from 0.4% to 1.6%. Higher errors are recorded for lower aptitude angle of incident solar rays.

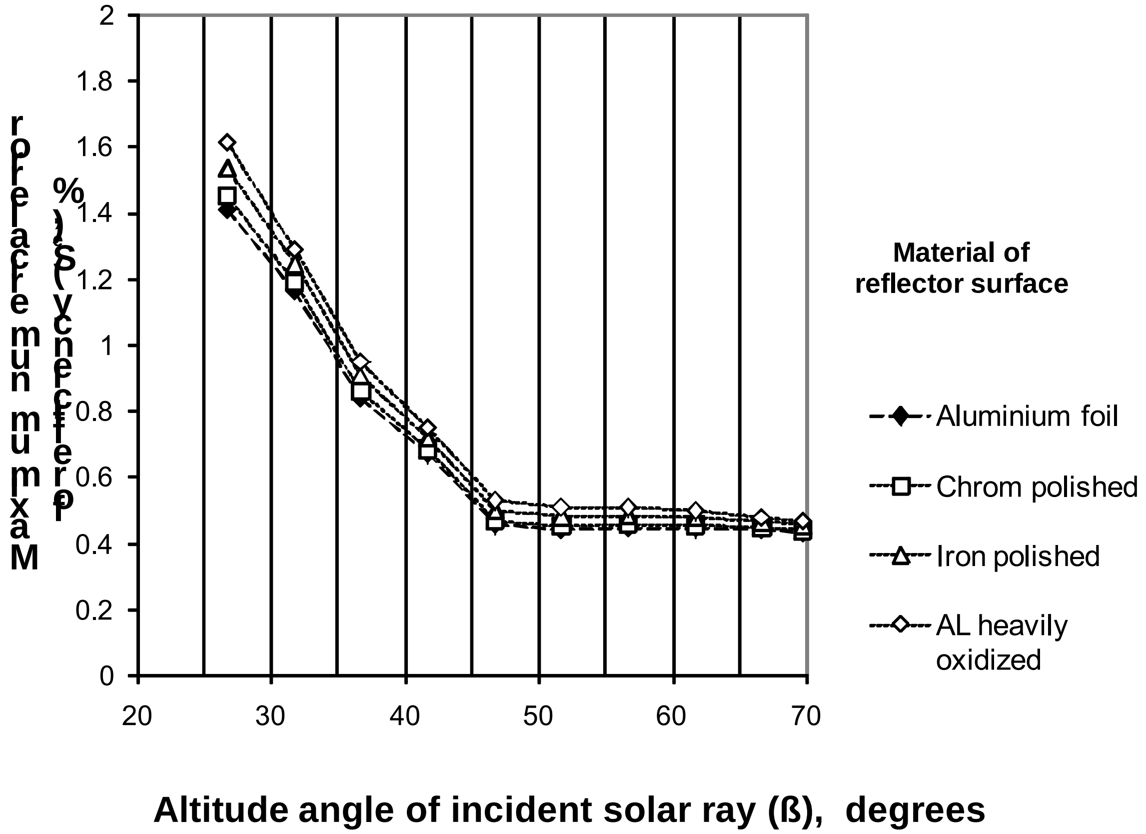

Fig.10 Maximum relative numerical error for efficiency as a function of the altitude angle of incident solar rays.

## CONCLUSION

In this paper, we present the investigations of the “long” solar concentrator that uses solar energy to generate heat. The concentrator is stationary trough, and has parabolic-cylindrical reflector surface. Its geometrical concentration depends on the concentrator aperture angle and type of energy production and is between 1.8 and 36.

Propagation of light rays inside the concentrator to reach the absorber surface was investigated by using CATIA software. We found that light rays may hit absorber surface without reflection from the reflector, with one reflection from the reflector, with two reflections from the reflector, with three reflections from the reflector, and with more than three reflections from the reflector.

We found that the highest percentage of aperture is that of the light rays that hit absorber with one reflection from reflector for the incident angles from $40^0$ to $50^0$.

For angles from around $50^0$ to $60^0$, the highest percentage of aperture is that of the light rays that hit absorber with two reflections from the reflector. For angles from around $60^0$ to $69.75^0$, the highest percentage of aperture is that of the light rays that hit absorber with three reflections from the reflector.

## ACKNOWLEDGMENT

This paper is a result of project 27003 of Ministry for Science of Republic of Serbia. We are grateful for their financial support.

## NOMENCLATURE

A = total area of the concentrator aperture (plane surface $T_WT_IF_IF_WT_W$ in Fig.1.) , $m^2$
$A_0$ = area of aperture surface where the light enters that hits absorber without any reflection from reflector, $m^2$
$A_1$ = area of entrance aperture surface for light that hits absorber with one reflection from reflector, $m^2$
$A_2$ = area of entrance aperture surface for light that hits absorber with two reflections from reflector, $m^2$
$A_3$ = area of entrance aperture surface for light that hits absorber with three reflections from reflector, $m^2$
$F_{>3}$ = area of entrance aperture surface for light that hits absorber with more than three reflections from reflector, $m^2$
r = light reflectivity from the surface of the reflector
e = efficiency of transfer of solar energy to concentrator absorber
$\beta_1$ = angle between absorber and horizontal direction
$\delta$ = aperture angle of the concentrator
$\varphi$ = latitude

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