Design and Simulation of a Solar Dish Concentrator with Spiral-Coil Smooth Thermal Absorber

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Abstract- The efficient conversion of solar radiation into heat at high temperature levels requires a use of concentrating solar collectors. The goal of this paper is to present the optical and thermal analysis of a parabolic dish concentrator with a spiral coil receiver. The parabolic dish reflector consists of 11 curvilinear trapezoidal reflective petals constructed by PMMA with silvered mirror layers and has a diameter of 3.8 m, while its focal distance is 2.26 m. This collector designed with commercial software Solidworks and simulated, optically and thermally in its Flow Simulation Studio. The optical analysis proved that the ideal position of the absorber is at 2.1 m from the reflector in order to maximize the optical efficiency and to create a more uniform heat flux over the absorber. In thermal part of the analysis, the energetic efficiency was calculated approximately 65%, while the exergetic efficiency is varied from 4% to 15% according to the water inlet temperature. Moreover, other important parameters as the heat flux and temperature distribution over the absorber are presented. The pressure drop of the absorber coil calculated at 0.07 bar, an acceptable value that was validated with the theoretical one.

Keywords: Solar dish reflector, spiral-coil absorber, optical analysis, thermal analysis, Solidworks

I. INTRODUCTION

Energy consumption has increasing rate worldwide because of the new trends in lifestyle. With threats of global warming and increased energy cost, the use of renewable and sustainable energy sources is becoming more and more popular. Solar energy is the most abundant and its usage is the more widespread. Solar collectors are heat exchanger devices which capture the incident solar irradiation and transform a part of this to useful heat. This heat is given to a working fluid in order to be transferred to the load or to the storage device. The temperature level of the working fluid is determines its exergy flow which is also a crucial parameters flow medium and high temperature applications. In order to increase the temperature of the working fluid and its exergy rate, concentrating collectors are used in many applications.

The solar thermal collectors have been widely used to concentrate solar radiation and convert it into medium-high temperature thermal processes. Low cost, two axis tracking solar dish with flat mirror system's (Solarux CSP) design and its advantages are described in this paper. In this paper, it has been focusing on air-conditioning, heating, and producing electricity by using Solarux CSP. The aim of this invention is to use planar mirrors instead of parabolic mirrors in order to reduce cost and design a system that can be manufactured easily, can be constructed on every kind of terrain (rocky, plain etc.) and can be used by third world countries [1,2]. The solar concentrating collectors operate by focusing incident solar radiation onto a small area known as the focal area. Many classes of concentrating collectors are available, each with different concentrating ratios and maximum absorber temperature, depending on the type of application. Generally, solar thermal utilization can be categorized into low-temperature solar concentrating system and high temperature solar thermal systems. The low temperature solar systems, which may not involve sunlight concentration, have lower conversion efficiency. The high temperature solar thermal systems, 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 concentrator for medium temperature applications. The same researchers [6] developed mathematical model of solar parabolic dish concentrator based on square flat facets applied to polygeneration system. Traditionally, the optical analysis of solar concentrators has been carried out by means of computer ray-trace programs. This 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 was to design solar concentrator for production of portable hot water in rural India. They used the 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°C, 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°C. 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 solar solar concentrator. Quanjun et al. [12] have investigated on the photo – thermal conversion efficiency in order to improve the cost effectiveness of the 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 show that outlet water temperature and energy input linearly increase with increasing direct normal irradiation, but energy output non-linearly increases with increasing direct normal irradiation. Their results also show that the maximum energy efficiency is 52.12% when the direct normal irradiation is 800 W/m². Eswaramoorthy and Shanmugam [13] have investigated the thermal efficiency of solar cooker with the diameter of the parabola equal to 3.56 m and the parabolic concentrator surface area of 10.53 m². Their results show that the thermal efficiency of the system was found to be 60%. K.S. Reddy et al. [14] has experimentally investigated 20 m² solar parabolic dish collector in order to study its performance with the modified cavity receiver. The average value of the overall heat loss coefficient was found to be about 356 W/m². K. Jones and Wang [15] computed the flux distribution on a cylindrical receiver of parabolic dish concentrator using geometric optics method. The parameters such as concentrator surface errors, pointing offset errors and finite sunshape were considered in the geometric optics method. Thakkar et al. [16] have investigated possible use of parabolic dish collector in process industries. They presented performance assessment mathematical model for heating application using thermal oil. R. Blázquez et al. [17] describes optical test for the DS1 (parabolic Stirling dish) prototype carried out by CTAER. The aim of this investigation was to characterize the DS1 prototype optical parameters. For this purpose the real and the theoretical flux distribution was calculated on a target placed at the focal plane. The theoretical flux distribution was obtained by photogrammetry technique and ray tracing tools; the real flux distribution was measured by photographic flux mapping technique of lunar images. The results comparison showed that the dish surface had an average optical error of 2.5 mrad and an estimated spillage value of 7%, for this geometry. Zhigang et al. [18] have predicted of the radiation flux distributions of the concentrator - receiver system by Monte Carlo ray tracing. The ray-tracing method was first validated by experiment, then the radiation flux profiles on the solar receiver surface for faceted real concentrator and ideal paraboloidal concentrator, irradiated by Xe-arc lamps and real sun, for different aperture positions and receiver shapes are analyzed, respectively. The resulted radiation flux profiles are subsequently transferred to a CFD code as boundary conditions to numerically simulate the fluid flow and couple with optical properties to predict radiation performance of dish solar concentrator/cavity receiver systems. The effects of sun shape and surface slope error have been studied and the corresponding probability models are introduced in this paper. Based on the concept of equivalent radiation flux, an upside-down pear cavity receiver is proposed in view of directional attributes of focal flux

In this paper authors, after conducting large number of numerical simulations and various geometrical configurations of the receiver, accepted the spiral type of the solar receiver. The first step of the analysis includes an optical optimization in order to predict the distance between reflector and spiral coil. The next part is the determination of the energetic and exergetic efficiency of the collector for a range of water inlet temperature. Other important parameters are presented with diagrams and figures from the simulation tool, which is Solidworks flow simulation studio. More specifically the temperature over the absorber and inside the water is given. The heat flux distribution over the down part of the absorber and along the spiral is presented. The pressure drop between inlet and outlet and the velocity of the water in every location are presented. By giving all these information, the problem is fully analyzed and the operation is explained with many details. The next figures shows.

II. GEOMETRICAL MODEL OF SOLAR PARABOLIC DISH CONCENTRATOR

In this paragraph, the model description is presented. Figures of the designed system are given (Figures 1-4) and the basic parameters of the geometric parameters of the system are shown in table1. The ideal optical configuration for the parabolic concentrator is a continuous paraboloidal mirror (shown on Figure 1), which is very expensive to fabricate, and it costs escalating rapidly with aperture area. A continuous parabolic dish surface can be approximated by a discrete surface consisting of 11 curvilinear trapezoidal reflective petals situated in a single parabolic frame (shown on Figure 2), dramatically reducing the system cost, while still allowing for concentration ratios at a level suitable for a wide range of medium to high temperature applications. Dimensions of reflecting surface in solar dish concentrator are determined by desired power at maximum levels of
Direct normal radiation and efficiency of collector conversion.

Mathematical representation of solar parabolic dish concentrator is paraboloid that can be represented as a surface obtained by rotating parabola around axis, which is shown on Fig. 1. Our model of parabolic concentrator is designed with 11 curvilinear trapezoidal reflective petals. Mathematical representation of the reflective petal can be presented as the parabola segment shown in Figure 3. On Figure 4 is presented one curvilinear trapezoidal reflective petal, which is made from the PMMA (polymethyl methacrylate) with special reflective coating. Thickness of the petal is 3 mm.

Usually paraboloids that are used in solar collectors have rim angles from 10 degrees up to 90 degrees. The paraboloid 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° (our parabolic solar concentrator has the rim angle \( \Psi_{\text{rim}} = 45.6^\circ \)) are used for cavity receivers while paraboloids with large rim angles are most appropriate for the external volumetric receivers (central receiver solar systems).

Focal diameter ratio of our solar concentration system is 0.59. The model of solar parabolic concentrator (Figures 5 and 6) 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 to maximum concentration of solar radiation in the receiver at any point of time with minimal optical losses of incident radiation. On figures are presented CAD renderings of our system, which is under construction. After finishing construction of the system we shall continue with the experimental verification of the system in the solar accredited laboratory of Faculty of Mechanical Engineering in Nis.

Design parameters of the solar parabolic dish concentrator are shown in Table 1. The table gives analytical determination of every parameter because there are many geometric characteristics in the designed model. It is essential to state that the receiver has a spiral coil shape with a smooth geometry.

### TABLE I. DESIGN PARAMETERS OF THE SOLAR PARABOLIC DISH CONCENTRATOR

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Numerical Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrator aperture diameter</td>
<td>3.8</td>
<td>[m]</td>
</tr>
<tr>
<td>Collector aperture diameter ( A_a )</td>
<td>10.28</td>
<td>[m²]</td>
</tr>
<tr>
<td>Surface area of parabolic dish</td>
<td>21.39</td>
<td>[m²]</td>
</tr>
<tr>
<td>Focal-diameter ratio ( (f/D) )</td>
<td>0.6</td>
<td>[-]</td>
</tr>
<tr>
<td>Direct beam radiation ( G_b )</td>
<td>800</td>
<td>[W/m²]</td>
</tr>
<tr>
<td>Receiver diameter ( d_r )</td>
<td>0.4</td>
<td>[m]</td>
</tr>
<tr>
<td>Reflectivity of segmented petals</td>
<td>0.88</td>
<td>[-]</td>
</tr>
<tr>
<td>Focal distance ( f )</td>
<td>2.26</td>
<td>[m]</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>0.2</td>
<td>[m]</td>
</tr>
<tr>
<td>CR( g )</td>
<td>37.1</td>
<td>[-]</td>
</tr>
<tr>
<td>CR( \psi )</td>
<td>35.6</td>
<td>[-]</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>1.9</td>
<td>[m]</td>
</tr>
<tr>
<td>( \Psi )</td>
<td>45.6</td>
<td>[°]</td>
</tr>
<tr>
<td>Depth of the concentrator</td>
<td>0.399</td>
<td>[m]</td>
</tr>
</tbody>
</table>

III. COMPUTATIONAL DOMAIN AND SIMULATION
The examined model is given in figure 7. The reflector and the absorber are shown in this figure because these are the two parts of the computational domain. The solar rays are also given in this figure. Figure 8 shows only the coil geometry. The inlet of the flow is the point “A” in Figure 8 and the outlet is the point “B” in the same Figure. The vacuum in the reflector is made for the bracket of the coil. Only these two parts are used in the simulation in order to make a simpler model.

Solidworks flow simulation studio combines optical and thermal analysis together and for this reason is ideal for this kind of simulation. The next tables give the main parameters of the simulation. Typical values were used in order to simulate conditions similar to the reality [21]. The environment temperature has assumed to be 10°C in order to simulate difficult ambient conditions with high heat losses.

### TABLE II. SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Title</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate</td>
<td>m</td>
<td>0.04kg/s</td>
</tr>
<tr>
<td>Solar beam radiation</td>
<td>G_s</td>
<td>800W/m²</td>
</tr>
<tr>
<td>Reflectance</td>
<td>ρ</td>
<td>0.8</td>
</tr>
<tr>
<td>Absorbance</td>
<td>α</td>
<td>0.8</td>
</tr>
<tr>
<td>Emittance</td>
<td>ε_ε</td>
<td>0.1</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>T_amb</td>
<td>10°C</td>
</tr>
<tr>
<td>Air-receiver convection coefficient</td>
<td>h_ar</td>
<td>10 W/m²K</td>
</tr>
</tbody>
</table>

In the flow simulation studio, the user has to determine the simulation conditions. First of all an internal analysis was selected because the water flows inside the tube. After this part the user selects that there is conduction in solids and the existence of solar irradiation. The radiation is selected to be constant and vertical to the aperture of the reflector. After this part the material was selected. Copper is selected for the absorber and a special mirror material for the reflector. Water is the working fluid that selected in this simulation. The mesh of the model was created by Solidworks with emphasis in fluid cells refinement.

The next important step is the boundary conditions determinations. In the inlet of water the flow mass rate and the uniform temperature were selected. After this, the static pressure in the outlet of the tube was set to be environmental. The last boundary condition is the heat convection between the coil outer surface and the environment. It is important to say that for determining a different operating condition, the water inlet temperature was changed in the proper boundary condition. After this step, the radiation surfaces were selected. The reflector was set to be a symmetrical surface in order to reflect the rays. Also, in the ray trace method the reflections were set to be forward. For the outer coil surface, new radiation surfaces were created by setting the suitable emissivity and absorbance.

The last part is the set of the proper goals. The global fluid and solid temperature levels selected as the first goals, because these goals helps the program to converge better. Moreover, the bulk average temperature in the outlet of the coil was selected as a goal. Furthermore, the solar energy captured by the coil was selected as goal, a goal that is very useful for the optical optimization. Finally, the mean coil temperature was selected as a goal. By changing the inlet temperature of the water, the collector was examined in various operating conditions. Also, by changing the distance between the coil and the reflector, the optical analyses were done.

Other collector types have been also analyzed with Solidworks flow simulation studio. A flat plate collector [26] and a evacuated tube collector [27] have been analyzed with focus on the thermal part of the analysis. A parabolic trough collector [28] have analyzed optical and thermally with very good results.

In this section, the basic equations that used for analyzing the results are presented. These equations are related to thermal, optical and exergetic efficiency of the collector.

The useful energy is calculated by equation (1), if the water outlet temperature is known:

\[
Q_u = m \cdot c_p \cdot (T_{out} - T_{in})
\]  

The total available solar radiation is calculated as:

\[
Q_s = A_u \cdot G_s
\]  

The thermal efficiency is given by equation (3):

\[
\eta_{th} = \frac{Q_u}{Q_s}
\]  

The optical efficiency is calculated through the goal of coil absorbed solar radiation:

\[
\eta_{opt} = \frac{Q_{abs}}{Q_s}
\]  

The absorbed solar energy from the receiver is given by the next equation:

\[
Q_{abs} = \eta_{opt} \cdot Q_s
\]  

The exergetic efficiency is calculated from equation (6):

\[
\eta_{ex} = \frac{E_u}{E_s}
\]  

The exergy output is given by the next equation [22-23]:

\[
E_u = \dot{m} \cdot c_p \cdot \left( T_{out} - T_{in} \right) - T_{amb} \cdot \ln \left( \frac{T_{out}}{T_{in}} \right)
\]  

\[
E_s = \dot{m} \cdot c_p \cdot \left( T_{in} - T_{out} \right)
\]
The useful exergy from the working fluid is the useful heat diminished by the entropy generation of the process. This is the maximum possible work that can be produced, if this heat is the source of a canto cycle.

The solar radiation exergy is given by Petela type [24]:

\[
E_s = Q_s \left[ 1 - \frac{4}{3} \left( \frac{T_{am}}{T_{sun}} \right) + \frac{1}{3} \left( \frac{T_{am}}{T_{sun}} \right)^3 \right].
\]

The sun temperature is selected to be 4350K, which is the 75% of the sun temperature in its outer layer. This is an assumption that has been taken into a great number of studies [25]. Moreover the use of the Petela formula is very discussed issues worldwide because it is difficult to determine the exact available exergy form the sun. Newer models take into consideration other geometrics characteristics of the sun, as the incident angle. Badescu [29] have proposed the use of sun geometric characteristic in order to determine better the exergy of solar radiation. However, the examined collector operates with a full tracking system which minimizes the incident angle and the Petela formula is the proper one for the analysis.

IV. OPTICAL ANALYSIS AND OPTIMIZATION

After the system design, the next step is the optical analysis and optimization of the system. More specifically, it is essential to predict the most suitable geometry for maximizing the solar energy utilization. An optimization is useful in order to predict the optimum distance between the coil and the absorber. By locating the coil in the focal point of the dish, all the solar rays will be concentrated there something that is not the preferable. The reason is because the solar radiation should be concentrated in all the part of the coil in order to heat all the water inside it and to be captured by a better way. So, the coil was placed closer to the reflector in order to create a more uniform heat flux distribution and to maximize the intercept factor. Figure 9 shows the optimization of this distance. The intercept factor \( \gamma \) is fully connected with the optical efficiency by the next equation:

\[
\eta_{opt} = \gamma \cdot \rho \cdot \alpha
\]

Where \( \rho \) is the reflectivity of the mirror and \( \alpha \) absorbance of the coil.

Figure 3 proves that the optimum distance is 2100mm, lower than the focal length. In this distance the intercept factor is 0.96 and the optical efficiency 0.676. This is a very important result for solar dish collectors. The reflectance (\( \rho \)) and the absorbance (\( \alpha \)) are kept constant and for this reason the optical efficiency and the intercept factor are proportional amounts. Figure 4 depicts the heat flux distribution over the down part of the coil. The maximum heat flux is observed close to the center but no to the center. The reason for this result is explained to the distance optimization. By locating the coil closer to the reflector, the rays are not concentrated in the center, but in all over the geometry. This situation creates a more uniform distribution and faces the problems of very high values in the center of the solar dish absorber. Another interesting result is the lower heat flux concentration in a circular sector, something that explained by the missing part of the reflector in the respective region.

Figure 11 shows the heat flux distribution along the coil line. In the region 0-5m, the heat flux intensity has a constant increasing rate and in the region 5-8m this increasing rate in getting greater. After this point, the heat flux intensity makes a maximum point and after this point is decreasing. The maximum heat flux is close to the end, but about some centimeters before. More specifically, the total coil length is about 9 meters and the maximum heat flux is in 8.32m. Moreover, figure 12 shows the heat flux distribution as a function of the radius R from the center. The results are similar to them from figure 11. It is essential to state that every point of the spiral has a different radius and for this reason the line in figure 12 is continuous. This design creates a more uniform distribution close to the center. If all the solar energy delivered to one point, then the material would be faced problems and the water will not utilizes all this energy. It is essential to state that the region of the coil which is over the vacuum in the reflector has lower heat flux intensity, something very logical.
V. ENERGETIC PERFORMANCE OF THE COLLECTOR

The collector efficiency is depended by the operating conditions and especially by the water inlet temperature. Moreover, the exergetic efficiency of the collector is an important parameter, especially when the useful heat is used for high temperature applications. In this paragraph the thermal efficiency and the exergetic efficiency of the collector are presented and analyzed. Figure 13 shows these parameters as a function of the parameter \( \frac{(T_{\text{in}} - T_{\text{am}})}{G_b} \), a usual parameter for expressing the collector efficiency.

The next figures show the temperature distribution in the absorber and in the fluid. In all these figures the water inlet temperature has assumed to be 50°C. Figure 14 shows the temperature of the coil and of the fluid along the spiral coil. It is obvious that the temperature is getting greater and the difference between the solid temperature and the fluid temperature has an increasing rate. The reason for this phenomenon is the increasing rate of heat flux closer to the end of the coil. Figure 15 gives respective results as figure 14. In figure 14 the mean temperature in every place along the coil is given, while in figure 15 the exact temperature distribution over the down part of the coil is given. Figure 16 presents a horizontal cross section with the water temperature. The temperature difference in the water is about 34K from inlet to the outlet, while the absorber temperature reaches 93°C, an acceptable temperature value.

The next equations are the approximation of thermal efficiency (equation 10) and exergetic efficiency (equation 11) with least square method.

\[
\eta_{\text{th}} = 0.6651 - 0.0755 \left( \frac{T_{\text{in}} - T_{\text{am}}}{G_b} \right) - 3.4173 \left( \frac{T_{\text{in}} - T_{\text{am}}}{G_b} \right)^2 \tag{10}
\]

\[
\eta_{\text{ex}} = 0.0398 + 1.8051 \left( \frac{T_{\text{in}} - T_{\text{am}}}{G_b} \right) - 4.3757 \left( \frac{T_{\text{in}} - T_{\text{am}}}{G_b} \right)^2 \tag{11}
\]

From the above figure it is obvious that the thermal efficiency is not very affected by the inlet temperature. More specifically, for inlet temperature equal to ambient temperature at 10°C, the thermal efficiency is 66.5% and for water inlet temperature equal to 70°C the efficiency decreases only 2.5%. On the other hand the exergetic efficiency has a great increase, from 4% to 15% when the water inlet temperature varies from 10°C to 70°C. The next figures together (14,15,16) the results shows to be similar and to be validated to each other, something very important for the strength of the presented method.
Figure 16 shows the fluid temperature in vertical cross sections. It is obvious that the water is getting warmer while it is closer to the center of the helix. Figure 18 gives the exact fluid temperature distribution in the outlet of the coil. The water is warmer in the down part of the tube, because the solar radiation is concentrated in this part. The total temperature deviation is about 2K across this vertical cross section, a value that is not high. These results prove that temperature in a cross section can be assumed uniform with an error of about 1K.

Figure 19 shows the velocity of the water inside the tube. This parameter varies from 0.6m/s to 0.8m/s. While the water flows inside the tube, its velocity is getting greater in its right side, because this part has greater rotating velocity. This phenomenon is more intense closer to the center, where the flow rotation is greater.

The last figure gives the pressure drop in the spiral coil. While the water goes closer to the exit (cross sections closer to the center), its pressure is getting lower because of energy losses. The total pressure drop is about 0.07bar and a circulator is needed in order to cover this pressure drop. The pressure drop is a very important parameter because of the high length of the absorber. In every design, this parameter is taken into consideration because the energy consumption in circulator may add a great operation cost in the system.

CONCLUSIONS

In this study an innovative and low-cost solar dish receiver with a spiral coil absorber is analyzed optically and thermally. First of all the model was designed in Solidworks and after was simulated in its flow simulation studio. The optical analysis proved that the optimum distance between reflector and coil is 2100mm, lower than 2260mm which is the focal length. This result leads to maximum intercept factor and to a more uniform heat flux distribution.

The energetic analysis proved that the collector performs well in great range of operating conditions. Its exergetic efficiency is getting greater with the higher inlet water temperature, a result which makes this collector ideal for higher temperature applications as solar cooling, electricity production and polygeneration in buildings. Analytical approximations for thermal and exergetic efficiencies are presented in the text.
In the deeper analysis of the collector, the heat flux is maximum close to the center but not in the center. More specifically, the total helix length is 9m and the maximum heat flux is in the region close to 8.32m. On the other hand, the temperature of the coil is maximum in the end of the coil. Moreover, the pressure drop along the spiral coil is calculated at 0.07bar, an acceptable value that indicated the use of a small circulator in the system.

For further work, thermal oil or air can be tested in order to operate this collector in higher temperature levels. In this analysis water was tested as working fluid, because it is the more usual fluid for thermal processes.

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