DESIGN, SIMULATION, AND OPTIMIZATION OF A SOLAR DISH COLLECTOR WITH SPIRAL-COIL THERMAL ABSORBER

by

Saša R. PAVLOVIĆ [a*], ***Evangelos A. BELLOS*** [b], ***Velimir P. STEFANOVIĆ*** [a], ***Christos TZIVANIDIS*** [b], ***and Zoran M. STAMENKOVIĆ*** [c]

[a] Department of Energetics and Process Technique, Faculty of Mechanical Engineering, University in Nis, Nis, Serbia
[b] Thermal Energy Department, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece
[c] Laboratory for Intelligent Production Systems, Department of Energetics and Process Technique, Faculty of Mechanical Engineering, University in Nis, Nis, Serbia

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The efficient conversion of solar radiation into heat at high temperature levels requires the use of concentrating solar collectors. The goal of this paper is to present the optical and the thermal analysis of a parabolic dish concentrator with a spiral coil receiver. The parabolic dish reflector consists of eleven curvilinear trapezoidal reflective petals constructed by poly (methyl methacrylate) with silvered mirror layer and has a diameter of 3.8 m, while its focal distance is 2.26 m. This collector is 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 relative 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 is calculated at 0.07 bar, an acceptable value.

Key words: *dish reflector, spiral-coil absorber, optical analysis, SolidWorks, thermal analysis*

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 that 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 determines its exergy flow which is also a crucial parameter for 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 useful heat for various thermal processes. Characteristics of solar thermal collec-

* Corresponding author; e-mail: saledoca@gmail.com

tors, especially the concentrating type, are well established in research literature and have many applications in industry and for domestic water heating, and steam generation [1, 2]. The operation principle of solar concentrating collectors is the focusing the incident solar radiation onto a small area known as receiver. Many types of concentrating collectors are available, with various concentrating ratios and different operating temperature levels. Linear parabolic collectors, compound parabolic collectors, Fresnel collectors, and solar dish collectors are the most widespread concentrated collectors. Generally, solar thermal utilization can be separated to low, medium, and high temperature systems. The low temperature solar systems, which operate without sunlight concentration, have low conversion efficiency and they are used in domestic applications. The medium and high temperature solar thermal systems, which require sunlight concentration, have higher conversion efficiency [3, 4] and they can used in great variety of applications.

During the last few years, the solar dish collectors are the concentrated collectors with over interesting studies because there are numerous designs for the absorber shape (spiral coils, cavities, tubes, *etc.*). Pavlović *et al.* [5] presented a mathematical and physical model of the new offset type parabolic concentrator with a spiral coil absorber for calculating its optical performance. The designed parabolic concentrator is a low cost solar concentrator for medium temperature applications. The same researchers [6] developed also a mathematical model of a solar parabolic dish concentrator based on square flat facets, which is able to be constructed easily with low cost. Many other studies related to solar dish collectors are focused on the optical analysis because this is fully depended by the design of the collector. 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.

Saleh Ali *et al.* [7] have presented an interesting study that aims to develop a 3-D static solar concentrator that can be used as a low cost technology 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. Optimization of the concentrator profile and geometry is carried out to improve the overall performance of system. Kaushika and Reddy [8] used a satellite dish of 2.405 m diameter with aluminum frame as a reflector to reduce the weight of the structure and the cost of the solar system. In their solar system, the average temperature of the produced vapor was 300 °C, when the absorber was placed at the focal point. The final cost of this system was about US$ 950. Reddy *et al.* [9] has experimentally investigated a 20 m^2 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/m^2. Jones and Wang [10] 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 sunshape were considered in the geometric optics method. Pavlović *et al.* [11] presented an optical design with a ray tracing analysis of solar dish concentrator composed of twelve curvilinear trapezoidal reflective facets. The goal of this paper is to present optical design of a low-tech solar concentrator that can be used as a potentially low-cost tool for laboratory-scale research on the medium temperature thermal processes, cooling, industrial processes, and polygeneration systems.

In this paper authors, after conducting large number of numerical simulations [5, 6, 11] and various geometrical configurations of the receiver, they decided to analyze the spiral type absorber. The main goal of the presented analysis is to determine the efficiency of the examined collector and to present results which explain its operation. The model was designed in the SolidWorks and was simulated in its flow simulation studio, a CFD solver based on the finite volume method. The first step of the analysis includes an optical optimization in order to predict the distance between reflector and spiral coil. The other geometry parameters, as absorber and reflector diameter, have been examined in previous works [11]. The next part is the determination of the energetic and exergetic efficiency of the collector for a range of water inlet temperature level. Moreover, the heat flux distribution over the down part of the absorber and along the spiral is presented. Other parameters as the temperature distribution over the coil and inside the water, the fluid velocity distribution and the pressure drop are given in order to explain the heat transfer phenomena inside the absorber. By presenting all these information, the solar collector is fully analyzed and its operation is explained with many details.

Basic features of the concentrating solar collector

The examined solar collector is now presented by emphasizing in the reflector design. Figure 1 shows the examined model. The total assembly model designed in SolidWorks is given in fig. 1(a) with the bracket. Figure 1(b) shows the model in the flow simulation studio, and fig. 1(c) the spiral-coil absorber model. The innovative design is based on the eleven curvi-linear trapezoidal reflective petals situated in a single parabolic frame. This design reduces dramatically the system cost, while it allows great concentration ratios demanded for medium and high temperature applications. The twelfth part of the reflector is missing because a bracket is needed in order to support the absorber. Mathematical representation of the reflective petal can be presented as the paraboloid dish. Design parameters of the solar parabolic dish concentrator are shown in tab. 1. This table gives the values of various parameters 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.

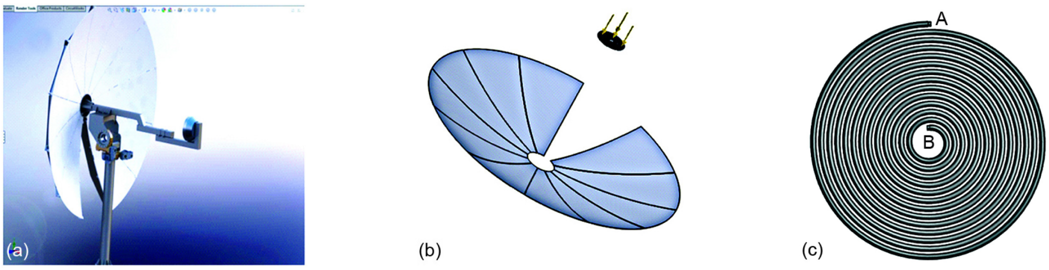

Figure 1. Solar collector design; (a) assembly model with all the parts, (b) simulation model, and (c) spiral-coil absorber

Table 1. Design parameters of the solar parabolic dish concentrator

Parameters	Values	Unit	Parameters	Values	Unit
Concentrator aperture diameter	3.80	[m]	Focal distance, f	2.26	[m]
Collector aperture diameter, A_a	10.28	[m^2]	Radius of parabolic dish reflector, R_1	0.20	[m]
Surface area of parabolic dish	21.39	[m^2]	Geometrical concentration ratio, C_{Rg}	37.1	[–]
Focal distance-reflector diameter ratio	0.59	[–]	Optical concentration ratio, C_{RO}	35.6	[–]
Solar beam radiation, G_b	800	[Wm^{-2}]	Radius of centered hole, R_2	1.90	[m]
Receiver diameter, D_r	0.40	[m]	Rim angle, Ψ	45.6	[°]
Reflectivity of segmented petals, ρ	0.88	[–]	Concentrator depth	0.40	[m]

It is important to state that the coil geometry has an optimum design in order to capture high irradiation amount with a relative uniform distribution. In fig. 1(c), the inlet of the flow is the point “A” and the outlet is the point “B” in the same figure. By this design the heat transfer in the fluid is optimum, because the hotter fluid is closer to the end of the coil where the heat flux intensity is greater.

Mathematical background

In this section, the basic equations that describe the examined model are given. These equations are related to thermal, optical, and exergetic efficiency of the solar collector. The thermal efficiency of the collector is given by eq. (1):

$$\eta_{\mathrm{th}} = \frac{Q_{\mathrm{u}}}{Q_{\mathrm{s}}} = \frac{m c_p (T_{\mathrm{out}} - T_{\mathrm{in}})}{A_{\mathrm{a}} G_{\mathrm{b}}} \tag{1}$$

The useful heat, Q_{u}, is calculated as the energy that captured by the water, and the solar energy, Q_{s}, is the available beam radiation in the dish aperture. The optical efficiency is calculated as the ratio of absorbed solar energy from the coil to the total solar radiation:

$$\eta_{\mathrm{opt}} = \frac{Q_{\mathrm{abs}}}{Q_{\mathrm{s}}} \tag{2}$$

The exergetic efficiency of the collector is calculated from eq. (3):

$$\eta_{\mathrm{ex}} = \frac{E_{\mathrm{u}}}{E_{\mathrm{s}}} = \frac{\dot{m} c_p \left[(T_{\mathrm{out}} - T_{\mathrm{in}}) - T_{\mathrm{am}} \ln\left(\frac{T_{\mathrm{out}}}{T_{\mathrm{in}}} \right) \right]}{Q_{\mathrm{s}} \left[1 - \frac{4}{3}\left(\frac{T_{\mathrm{am}}}{T_{\mathrm{sun}}} \right) + \frac{1}{3}\left(\frac{T_{\mathrm{am}}}{T_{\mathrm{sun}}} \right)^4 \right]} \tag{3}$$

The useful exergy, E_{u}, from the working fluid is the useful heat diminished by the entropy generation of the process [12, 13]. This is the maximum possible work that can be produced, if this heat is the heat source of Carnot cycle. The exergy flow of solar radiation, E_{s}, is calculated according to Petela theory [14]. The Sun temperature is selected to be 4350 K, which is the 75% of the real Sun temperature in its outer layer. This is an assumption that has been taken into a great number of studies [15].

Simulation of the model

SolidWorks flow simulation studio combines optical and thermal analysis together and for this reason is ideal for this kind of simulation studies. Table 2 gives the main parameters of the simulation. Typical values were used in order to simulate conditions similar to the reality [16]. The environment temperature has assumed to be 10 °C in order to simulate difficult ambient conditions with high heat losses.

Table 2. Simulation parameters

Title	Parameter	Value
Mass flow rate	m	0.04 kg/s
Solar beam radiation	G_{b}	800 W/m^2
Reflectance	ρ	0.88
Absorbance	α	0.80
Receiver emittance	ε_{r}	0.10
Ambient temperature	T_{am}	10 °C
Air convection coefficient	h_{air}	10 W/m^{2}K

In the flow simulation studio, the user has to determine many simulation conditions. First of all, an internal analysis is selected because the water flows inside the tube. After this, the user selects the existence of 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 determined. Stainless steel AISI 304 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 is created by SolidWorks with emphasis in fluid cells refinement. By making refinement in fluid cells, the convergence is better and the results are acceptable. About two million elements are used in the thermal simulation of the coil. In the optical analysis that is made also with flow simulation tool, two millions of solar rays were selected in order to simulate sufficiently the problem.

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 Sun rays. Also, in the ray trace method the reflections were set to be forward for having the desirable results. For the outer coil surface, new radiation surfaces is created by setting the suitable emissivity and absorbance.

The last part is the set of the proper convergence goals. Global goals for the fluid and the solid temperature levels selected as the first goals, because these goals lead the solution to convergence. Moreover, the bulk average temperature in the outlet of the coil and the mean coil temperature are selected as surface goals. Furthermore, the solar energy captured by the coil is selected as a surface goal, a very useful parameter for the optical optimization. By changing the inlet temperature of the water, the collector is examined in various operating conditions. Also, by changing the distance between the coil and the reflector, the optical analyses are done.

SolidWorks flow simulation studio has also been used in many other studies of solar collectors. More specifically, flat plate collectors [17] and evacuated tube collectors [18] have been analyzed with emphasis on the thermal analysis. A parabolic trough collector [19-21] have analyzed optical and thermally with very good results. The methodology in these studies was similar to this one. Saravanan *et al.* [22] 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.

Optical analysis and optimization

After the initial system design, the next step is the optical analysis and the optimization of it. More specifically, it is essential to predict the most suitable design for maximizing the solar energy utilization. An optimization is made in order to predict the optimum distance between the coil and the reflector. By locating the coil in the focal point of the dish, all the solar rays will be concentrated on a region close to the coil center, something that is not the preferable. The desired heat flux is the uniform heat flux in order the absorber temperature to be lower and the heat losses not to be great. So, the coil is placed closer to the reflector in order to create the demanded heat flux distribution and to maximize the intercept factor. Figure

2(a) shows the optimization of this distance. The intercept factor, γ, is fully connected with the optical efficiency according to eq. (4):

$$\eta_{\text{opt}} = \gamma \rho \alpha \tag{4}$$

where ρ is the reflectivity of the mirror, and α – the absorbance of the coil.

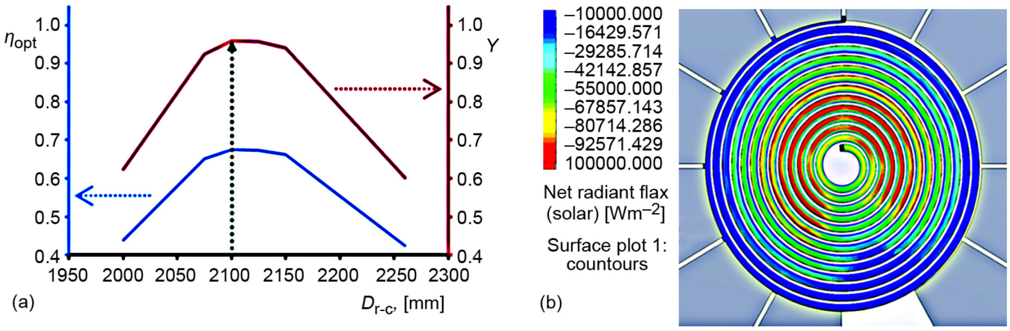

Figure 2. Optical analysis of the collector; (a) optimization of the coil-reflector distance, (b) heat flux distribution of absorbed solar energy in the absorber down part

Figure 2(a) proves that the optimum distance is 2.1 m, lower than the focal length of 2.26 m. In this distance, the intercept factor is 0.96 and the optical efficiency 0.676. This optimization is important for all the concentrated collector with dish reflectors. The reflectance and the absorbance are kept constant in the design optimization method and for this reason the optical efficiency and the intercept factor are proportional amounts. Figure 2(b) 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 concentration values close to the center of the coil 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 3(a) shows the heat flux distribution along the coil line. In the region 0-5 m, the heat flux intensity has a constant increasing rate, and in the region 5-8 m this increasing rate in getting greater. After this region, the heat flux intensity makes a maximum point and after this point, the intensity starts decreasing. The maximum heat flux is close to the end of the coil, but about some centimeters before. More specifically, the total coil length is about 9 m and the maximum heat flux is in 8.32 m. Moreover, fig. 3(b) shows the heat flux distribution as a function of the radius, R, from the center. The results are similar to these of fig. 3(a). It is essential to state that every point of the spiral has a different radius and for this reason the line in fig. 3(b) is continuous. These two figures, 3(a) and (b), present similar results and prove that there is connection between radius distance and length position along the spiral. Equations (5) and (6) give the spiral coil geometry as a function of parameter t, which is ranged from 0 π to 26 π. The presented design creates a relative uniform distribution close to the center. If the coil was located in the focal distance, then all the solar energy would be delivered to a small region, decreasing the efficiency and creating the danger of melting the coil material. 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 accepted:

$$x(t) = \left(0.4 - 0.35\frac{t}{26\pi}\right)\cos(t) \tag{5}$$

$$y(t) = \left(0.4 - 0.35\frac{t}{26\pi}\right)\sin(t) \tag{6}$$

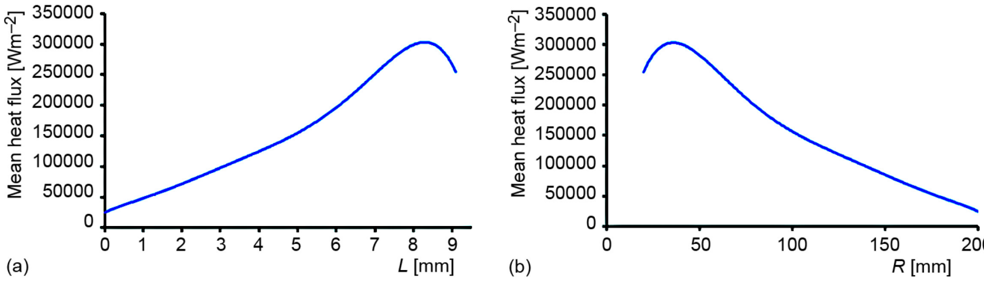

Figure 3. Heat flux distribution; (a) along the coil, (b) as a function of the distance from the center

Energetic performance of the collector

The collector efficiency is depended on the operating conditions and more specifically 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 4(a) shows these parameters as a function of the parameter $(T_{in} - T_{am})/G_b$, a usual parameter for expressing the collector efficiency.

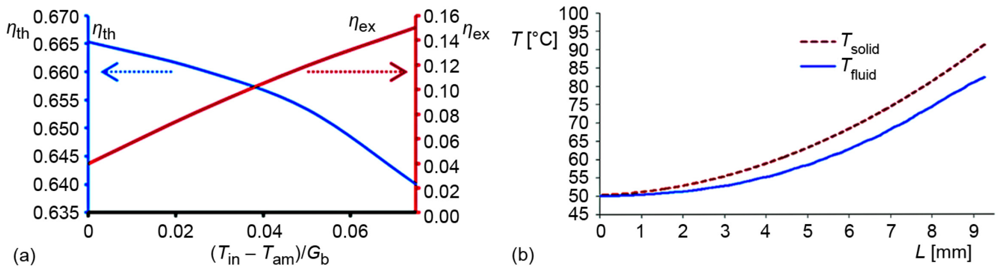

Figure 4. Collector performance; (a) thermal and exergetic efficiency, (b) temperature distribution of the absorber and the water

From fig. 4 it is obvious that the thermal efficiency is not very affected by the inlet temperature and it is approximately 65% in the examined conditions. 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.

Figure 4(b) shows the temperature distribution in the absorber and in the fluid. In all these figures the water inlet temperate has assumed to be 50 °C. Figure 4(b) shows the temperature of the coil and of the fluid along the spiral coil. It is clear 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 5(a) gives respective results as fig. 4(b). In fig. 4(b) the mean temperature in every place along the coil is given, while in fig. 5(a) the exact temperature distribution over the down part of the coil is given. Figure 5(b) is a horizontal cross-section and depicts the water temperature distribution. The temperature difference in the water is about 34 K from inlet to the outlet, while the absorber temperature reaches 93 °C, an acceptable temperature value. By analyzing these three figures together, 4(b), 5(a), and 5(b), the results show to be similar and to be validated one to each other, something very important for the strength of the presented method.

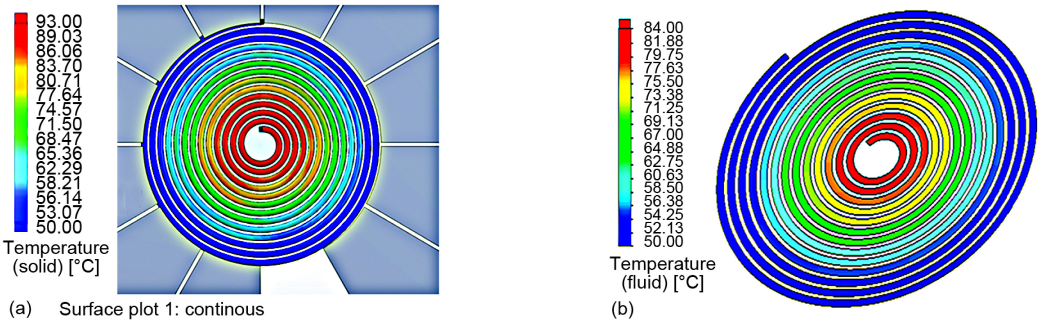

Figure 5. Temperature distribution; (a) over the down part of absorber, (b) on the water in a horizontal cut in the middle of the tube

Figure 6(a) 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 6(b) 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 2 K 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 1 K.

Figure 7(a) gives the velocity of the water inside the tube. This parameter varies from 0.6 m/s to 0.8 m/s. While the water flows inside the tube, its velocity is getting greater in

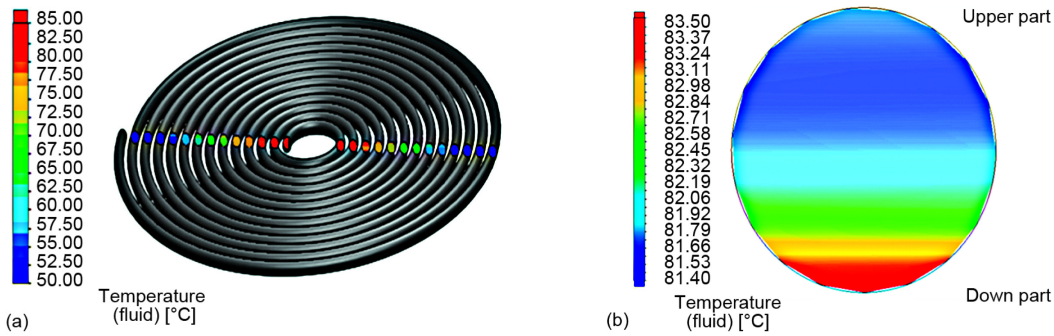

Figure 6. Water temperature distribution; (a) in cross sections of the spiral coil, (b) distribution in the cross section of the outlet; the upper part of the figure presents the hotter down part of the coil

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.

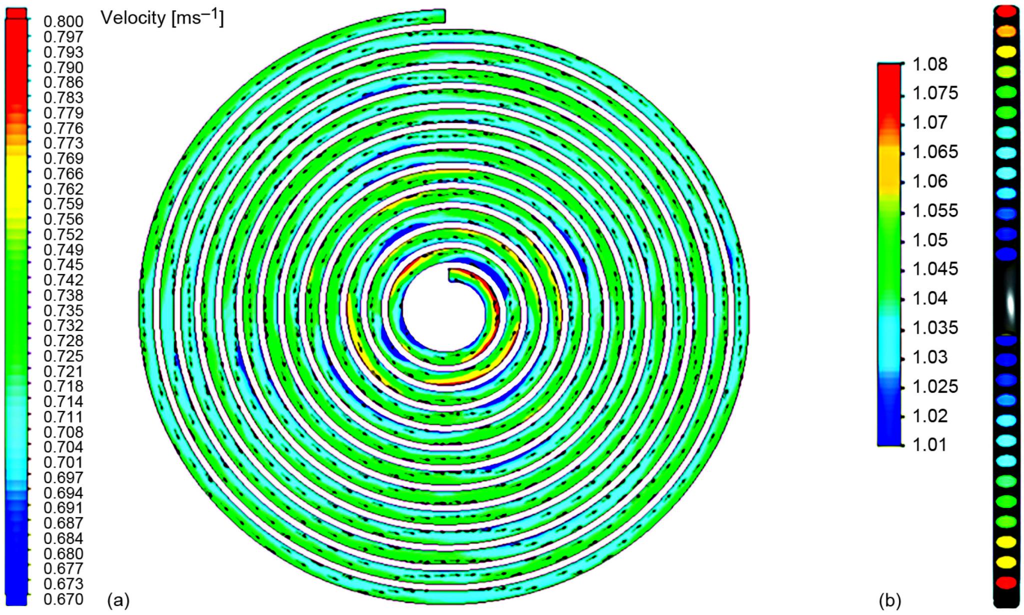

Figure 7. (a) Water velocity in a horizontal cut in the middle of the tube, (b) fluid pressure distribution in cross sections of the coil

Figure 7(b) 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 0.07 bar, 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 reflector with a spiral coil absorber is analyzed optically and thermally. This solar collector can be used in many applications, from domestic hot water applications to industrial processes. In the first part of this study, the model is designed in SolidWorks and after it is simulated in its flow simulation studio. The optical optimization of the collector proved that the ideal distance between reflector and coil is 2.1 m, lower than 2.26 m which is the focal length. This result leads to maximum intercept factor and to a relative uniform heat flux distribution.

The energetic analysis shows 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. More specifically, the thermal efficiency of the collector is calculated to be close to 65% for the examined conditions, while the exergetic efficiency increases with the water inlet temperature from 4% to 15%. Also, analytical approximations for thermal and exergetic efficiencies are presented in the text.

In the deeper analysis of the collector, the maximum heat flux is observed close to the centreof the coil but not there. More specifically, the total helix length is 9 m and the maximum heat flux is reached 0.68 m before the end. On the other hand, the maximum temperature of the coil is achieved in the end of the coil, something that is partly depended by the heat flux distribution. Moreover, the pressure drop along the spiral coil is calculated at 0.07 bar, an acceptable value that indicated the use of a small circulator in the system.

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Nomenclature

A – area, [m^2]
c_p – specific heat capacity, [kJkg^{-1}K^{-1}]
D_r – receiver diameter, [m]
$D_{r\text{-}c}$ – reflector coil distance, [mm]
f – focal distance [m]
G_b – solar beam radiation, [Wm^{-2}]
h_{air} – air-receiver convection coefficient, [Wm^{-2}K^{-1}]
L – coil length, [mm]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
Q – heat flux, [W]
R – distance from the center, [mm]
T – temperature, [°C]
t – spiral parameter, [–]
x – x-Cartesian co-ordinate, [m]
y – y-Cartesian co-ordinate, [m]

Greek symbols

α – absorbance, [–]
γ – intercept factor, [–]
ε – emittance, [–]
η – efficiency, [–]
ρ – reflectance, [–]

Subscripts and superscripts

a – aperture
abs – absorbed
am – ambient
ex – exergetic
in – inlet
opt – optical
out – outlet
r – receiver coil
s – solar
sun – Sun rays
th – thermal
u – useful

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