Parametric Study on the Thermal Performance of a Trapezoidal Cavity Absorber for a Linear Fresnel Solar Collector

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Abstract- A trapezoidal cavity receiver for a Linear Fresnel Solar Collector was investigated in this paper. Seven parameters were analyzed to visualize the effect of each one on the Output Thermal Power (OTP) in order to optimize it by finding the optimum dimensions. A Monte Carlo ray tracing method was used to predict the optics and energy behavior of the studied plant, then a mathematical program was developed to obtain the heat flux density distribution in absorber tubes. CFD simulation was carried out to determine temperature distribution on the absorber tubes. The effect of distance between Fresnel mirrors, absorber tubes diameter, distance between absorber tubes, and their position according to cavity depth and HTF velocity are evaluated. The cavity is considered to be under vacuum and Air/ Haynes 6B are the chosen couple HTF/Material tubes.

Keywords Trapezoidal cavity receiver, Linear Fresnel reflector, Ray tracing model, CFD simulation.

1. Introduction

Linear Fresnel reflector (LFR) systems are used for medium temperature solar thermal devices (100–400 °C) [1][2]. Although LFR systems are not efficient compared to Parabolic Trough Collector (PTC) and Parabolic Dish Reflector (PDR) [3], they are supposed to be a promising application for reducing manufacturing costs [4] [5], which is a limitation considering PTC technology. Additionally, LFR systems are known by easy maintenance, a stationary receiver and lower cost compared to PTC [4][6].

Lately, both the non renewable energy expected depletion and ecological matters engendered by their utilization [7][8] boost studies towards the use and improvement of renewable energy sources; among others, solar energy. Solar energy is presently used as a power source by the photovoltaic systems (PV) or thermal structures (at low and high temperature (CSP)) [9][10]. Previous researchers conducted studies on LFR plants conditions that influence the efficiency and performance. [11] Analyzed the latitude effect on the optimum orientation of a system consisting of 19 mirrors of 0.5m wide and spaced of 1m. [12] Analytically studied the radiation concentration process in LFR system. [13] Experimentally and numerically investigated the daily and the instantaneous performance in LFR of flat plate receiver with absolute collecting opening surface of 36 m2 and joined to 1 m3 volume of a storage tank. [14] Investigated a receiver cavity that forms a V shape in a LFR plant. Time, cavity width and the fluid and ambient temperatures are analyzed and optimized to enhance the efficiency. [15] Verified, with simplified ray-trace simulation, the receiver absorber tubes number and the inclination of side walls in the cavity. Cavity depth and rock wool insulation thickness were optimized employing CFD. [16] Studied the impact of ambient temperature, absorber temperature, cavity depth, insulation thickness, inclination of lateral sides, glass window and the emissivity of the selective absorption coating, on the performance of the receiver. [17] Evaluated, by quantifying cavity heat transfer rate and heat loss, the Copper absorber tubes position. The effect of cavity angle has been studied by [18], carrying out a CFD method for two cavity angles and [20] evaluated the effects of the cavity angle and the effect of the tube size on the total and radiation heat transfer rate through the absorber tubes.

The current work contribution is investigating and analyzing the influence of various parameters on absorber tubes Output Thermal Power (OTP) of a trapezoidal cavity receiver. A Monte Carlo ray tracing method, using Tonatiuh program, was employed for the simulation of the optics and energy comportment of the studied plant. When the solar concentrating system and the received direct solar rays were formed the results were safeguarded within divers binary files. Mathematica 9.0 was used for post treatment to get the heat flux density distribution in absorber tubes. To discover temperature distribution COMSOL Multiphysics 5.2a was utilized as Computational Fluid Dynamics (CFD) software.

2. Materials and Methods

The present investigation involved analyzing the influence of various parameters on absorber tubes OTP of a trapezoidal cavity receiver. The configuration was a trapezoidal cavity that encircles a four parallel pipe batch. This cavity receiver for a linear Fresnel solar collector had been usually analyzed by earlier scientists. [19] Studied and compared its thermal performance by studying the influence of the concentration ratio of Fresnel reflecting collector and selective surface coating on the absorber. [20] Analyzed the heat transfer rate and heat loss and evaluated, in different models, the cavity angle and the tube size effects. [21] Determined attained temperature by absorber tubes, considering a fixed time and location and [22] elaborated a study of a linear Fresnel solar collector, in terms of optical and thermal analysis.

2.1. Geometry

An illustrative drawing of the suggested cavity absorber for LFR system is exposed in Fig. 1. It employs 14 columns of Fresnel mirrors, on either side of the absorber. The under vacuum cavity, encloses four parallel pipes, and a located glass at the base of the receiver forms a cavity. The receiver initial dimensions were selected conforming to dimensions table given by [4] as shown in Table 1.

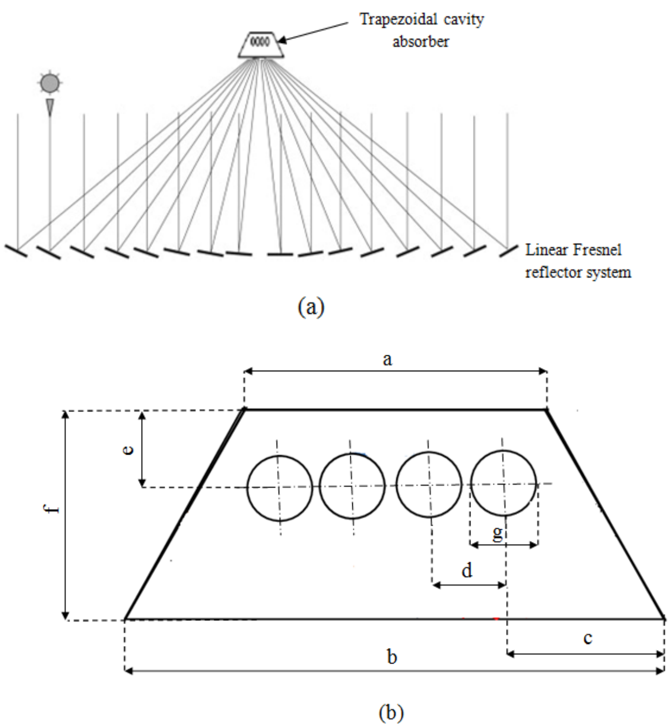


Fig. 1. illustrative drawing of the suggested cavity absorber for LFR system. (a) Full plant. (b) Geometry of the proposed cavity absorber.

Table 1. Initial dimensions of the trapezoidal receiver

Parameters	Dimensions (mm)
a	711.68
b	1231.3
c	503.15
d	75
e	40
f	150
g	50

The Fresnel mirrors' dimensions are one of studied parameters; indeed, distance of 900 mm between mirrors was kept constant, and variation was done on mirrors width. The receiver length is 250 mm. Angle cavity was also kept constant, concerning the parameters related to the receiver itself.

2.2. Design and simulation

In this study, seven parameters are investigated to examine each one's effect on the OTP to optimize it by finding the optimum dimensions. Identical to [21], sketch and simulation of the proposed plant were carried out by Tonatiuh. Mathematica 9.0 program was engendered for post processing binary files produced by Tonatiuh and, finally, temperature distribution was simulated in COMSOL Multiphysics 5.2a.

Using Tonatiuh, a ray tracing model was produced, as seen in Fig.2, which provides the form of the concentrating plant, the received solar rays, the reaction between the rays and the components of the system, and a choice of the results creation way [23]. 15 July 2015 at 13 pm (G.M.T) was chosen as the day and time of the study. Considering data provided by [24] the required DNI was selected. [25] Revealed that simulation software precision increases while implementing dynamic Sun shape instead of static one. In Tonatiuh, the Sun shape was constant so the pillbox one was selected. 5 000 000 sun rays were selected for simulations.

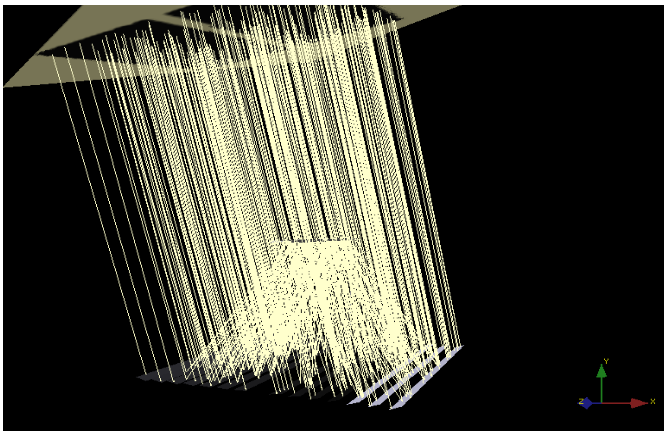


Fig. 2 Isometric view of the ray tracing model in Tonatiuh with 500 sun rays.

2.3. Estimate of solar flux distribution

Mathematica 9.0 program was generated for post processing binary files produced by Tonatiuh. The Mathematica program contains the following parts:

- Receiver dimensions and its number of division.
- Post-processing simulation: functions were used to determinate heat flux density distribution in absorber pipes. The formula used for that is:

HFD= (Total number of photons at the absorber tube × Power per photon) / The elementary area of the tube (1)

2.4. 3D simulation

To obtain temperature distribution in the four absorber tubes COMSOL Multiphysics 5.2a was utilized. A 3D numerical simulation was established with the interface of heat transfer in solids. This interface is to model conduction, convection, and radiation heat transfers. The study was realized using temporal study and laminar flow. Understanding absorbers thermal transfers is indispensable to properly model it. The four tubes contain a flowing heat transfer fluid (HTF); it absorbs solar energy, which is irradiated by Fresnel reflectors, so that fluid temperature increases. The heat transfer modes that appeared in the receiver were forced convection and radiation. Indeed, forced convection took place because of the speed of 0.25 m/s given to the HTF using fans to circulate it into absorber tubes; an insulation effect was created in the cavity by the creation of vacuum that does not annul radiative heat transfer, the only form of heat transfer present in vacuum. The concept of vacuum absorbers is already present for PTC [26] [27] [28]. Creating vacuum has many advantages such as high efficiency and small heat loss. However, it has some disadvantages such as technical difficulty and high cost [29]. A literature inspection proves that the authors studying a trapezoidal cavity absorber for LFR didn't deal with cavity under vacuum. They studied heat losses on the cavity in order to minimize it [4] [30] [20].

The heat flux densities found earlier in 2.3 were used in the boundary of each tube. As shown in Fig.3 a mesh controlled by physics with coarsest size was chosen for mesh generation freedom during the process.

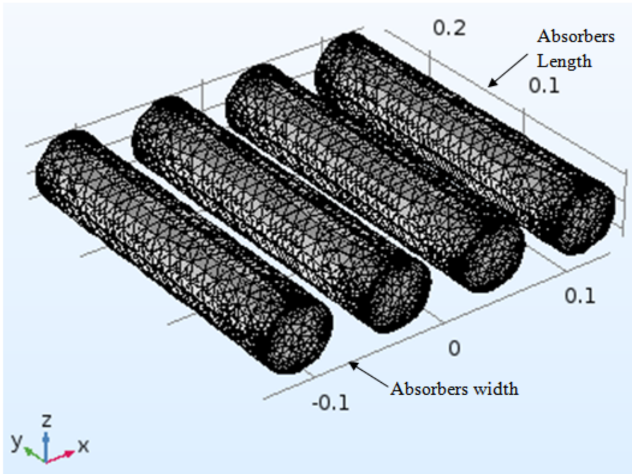


Fig.3 Absorber tubes entire mesh.

To calculate thermal power of each tube, the following formula was used:

$$Ptube_i = \dot{m}\, C_p\, (T_2 - T_1)\ \ [W]\ \ i=\{1,2,3,4\} \quad (2)$$

$\dot{m}$: Mass flow rate [Kg/s].

C_p : Specific heat capacity at constant pressure [J/Kg.K].

T_2 : Outlet temperature [K]. It is considered, in this study, as the HTF mean temperature at tubes outlet.

T_1 : Inlet temperature [K].

Tonatiuh takes into account reflection losses (due to the reflectivity of the absorber material). However, during the conjugated heat transfer simulation, using Comsol, radiative losses should be considered because these losses are a function of absorber temperature and are present under vacuum. Heat losses caused by radiation became the major mechanism for the receiver's heat transfer losses. In this case, tubes are radiating energy to the cooler surroundings; thus, after calculating the thermal power, the radiation losses are subtracted using the following formula:

$$Qtube_i = \varepsilon\, \sigma\, (Ttube_i^{4} - T_s^{4})\, Atube_i\ [W]\ \ i=\{1,2,3,4\} \quad (3)$$

ε: emissivity of material

σ: Stefan-Boltzmann constant (5.670 x 10^{-8}) $[W/m^2{\cdot}K^4]$

$Ttube_i$: $tube_i$ absolute temperature [K]

Ts : surroundings absolute temperature [K]

$Atube_i$: area of $tube_i$ $[m^2]$.

2.4.1. HTF selection

HTF is one of the essential components to ensure good performance and efficiency of CSP plants. It is required to maximize the performance of HTF while minimizing its cost. There are important thermo physical properties to consider while choosing HTF: low melting point, high boiling point, thermal stability, low vapor pressure (<1atm) at high temperature, chemical compatibility (low corrosivity) with metal alloys used to contain the HTF, low viscosity, high thermal conductivity, high heat capacity for energy storage, low cost, high availability and low toxicity, flammability, explosivity, and environmental hazard [31] [32].

Despite the fact that there are various HTFs, molten salts are very interesting ones as they melt at lower point (~200 °C), and they are thermally stable. The major issue of the molten-salts is their corrosivity with metal alloys [31]. In regards to liquid metals, they are stable at high temperature and provide superior heat transfer capability because of their large thermal conductivity [33] [32]. Their major limitation is their relatively low heat capacity [34]. In particular, liquid sodium has been tried in the SSPS experiments in Almeria in the 1980s where the plant took fire, withdrawn from service and this technology was suspended. An important feature of sodium is the security hazard given by the exothermic reaction with both air and water [32]. The use of liquid sodium must be accompanied by good security measures and meticulously respect safety standards. As regards synthetic oils, they are used, as HTF, for almost all commercial parabolic trough CSP plants. Synthetic oils are petroleum-based, so they are exhausted resources [35], expensive, highly environmentally hazardous, and very flammable [36].

In this study air was selected as HTF because it is cost-free and abundant [37]. Compared to molten-salts or liquid metals, thermal conductivity of air is low [38], but its superior flow property makes it advantageous in efficient heat transfer. It also has high flow properties in the conduits in a CSP plant [38] [31], due to its really low dynamic viscosity (~ 4 × 10-5 Pa s at 550°C).

2.4.2. Material of cylindrical absorbers

In order to make a relevant choice of the absorbers material, it is necessary to consider the corrosion behavior at high temperature between the HTF and chosen material. According to [39], who exposed iron-aluminum chromium alloys for 1008 h in air at 1100°C, the mass change values; for the alloys with mass content of chromium and aluminum between 1.9 and 9.7 wt% , and 5.8 and 16.2 wt%, respectively, were between 7 and 14 g/m2. [40] mentioned that commercial steels generally have, besides the planned alloying components, impurity elements; the existence of less noble metals than iron like silicon, aluminum and chromium contributes to an oxidation resistance for steel; however, the protective effect becomes negligible if their levels are very low. In contrast, metals more noble than iron like tin, copper and nickel, have small effect on the behavior of steel oxidation. [31] summarized, in a table, different alloys with different commonly used HTFs corrosion rates; as regards air, the table gives the same information given by [39] about air/ Fe-Al (5.8-16.2 wt%)-Cr(1.9 - 9.7 wt%) corrosion rate [31]. In the current study, the base-cobalt alloy, Haynes 6B was chosen as cylindrical absorbers material. Table 2 depicts the chemical composition and physical properties of the chosen material. Haynes 6B is known by its use in applications associated to wear and wear united to corrosion and/or high temperature [21] [41].

3. Results and Discussion

In this section, the effect of the seven studied parameters on the OTP is visualized and the obtained results are discussed.

3.1. Distance between Fresnel mirrors' effect, in relation to their width

Despite the fact that the number of operating and under construction LFR plants compared to other technologies is very low, LFR is a promising Concentrating Solar Power technology [12] [43]. Research is booming, and industrial applications are emerging from small industrial applications (heat, cold, electricity) to power plants ranging from 10 to 100 MW [43]. Optimizing parameters related to concentrators is one of the methods to increase the efficiency of concentrating solar power (CSP) technologies. Of these technologies, Linear Fresnel collectors (LFCs) are the least developed [30]. The current parameter reflects the optimal distance between mirrors taking into account their width. Several parameters related to Fresnel Mirrors have been previously studied by other researchers; [11] analyzed the effect of latitude on the optimum orientation of a system consisting of 19 mirrors of 0.5m wide and spaced of 1m. It has been found that recuperated flux by the East-West orientation (EW) is more sensitive to the time of day than with the North-South orientation (NS). The NS orientation of the mirrors axis is preferable except at very high latitudes and particular climatic case. [12] Analytically studied the radiation concentration process in a LFC. It has been found that mirrors width and gap should be differed through the field to improve the efficiency of the system; the width of the mirrors depends on their relative locations to the receiver, and shading and blocking require having a minimum space between mirrors. Authors also cited different solutions from published works that address the problem of shading, blocking, and deviations of reflected rays which do not have the same impact of centered reflectors in the field than those in the extremes. [13] experimentally and numerically investigated the daily and the instantaneous performance in LFR of flat plate receiver with absolute collecting opening surface of 36 m^2 and joined to 1 m^3 volume of a storage tank. It has been seen that 8.4 kW is the maximum useful heat production while 260 MJ is the maximum daily heat production.

The effect of distance between Fresnel mirrors according to their width on OTP of absorber tubes is depicted in Fig.4. As can be observed, the OTP is increasing with increase of Mirrors width/Distance between mirrors (%) until the latter reaches approximately 78%, and then a decrease of the OTP is noted.

Table 2. Chemical composition and physical properties of Haynes 6B [42].

Chemical composition, percent								
Cobalt	*Nickel*	*Silicon*	*Iron*	*Manganese*	*Chromium*	*Molybdenum*	*Tungsten*	*Carbon*
Balance	3.0 max	2.0 max	3.0 max	2.0 max	28.0 – 32.0	1.5 max	3.5 – 5.5	0.9 – 1.4

Physical properties					
Density (Kg/m^3)	**Melting range (°C)**	**Thermal conductivity (W/m.K)**	**Specific heat (J/Kg.K)**	**Specific Gravity**	**Electrical Resistivity (Microhm-m)**
8387	1265 to 1354	14.8	423	8.38	0.91

This may be attributed to optical losses such as shading and blocking noticed after this value. Mirrors width/ Distance between mirrors of 78% shows an OTP of 254,973 W. [44] optimized the geometry of LFCs by considering a target function that is the plant cost divided by the collected solar radiation in a year. It has been found in uniform optimization, where the mirrors have the same width and focal length and uniformly spaced, that the optimal configuration is given by (Mirrors width/ Distance between mirrors) = 82, 64%. Thus, despite the different target function optimized, the results are in good agreement with a relative error of 0,056147.

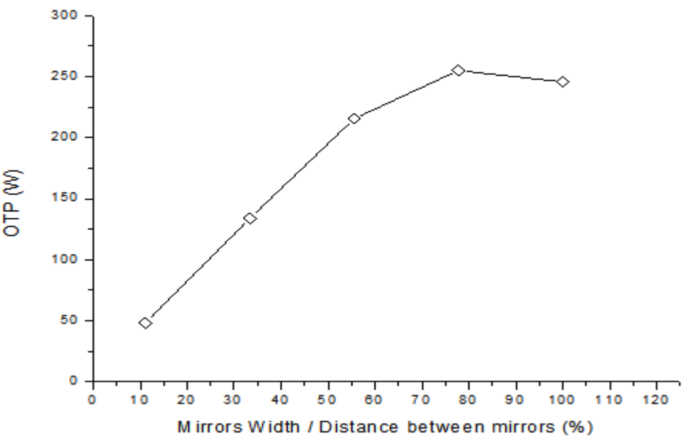


Fig.4 The relationship between Output Thermal Power of absorber tubes and Mirrors width/Distance between mirrors.

To investigate the effect of the parameter Mirrors width/Distance between mirrors (%), distance between mirrors was kept constant while mirrors width was the changed variable. [30] Concluded that the daily solar power increases while more mirrors are added or with the raise of mirror width; that is in good agreement with what is found in this article but with clarification of mirrors width limit according to the distance between mirrors which must not be exceeded in order to avoid optical losses.

3.2. Receiver Parameters

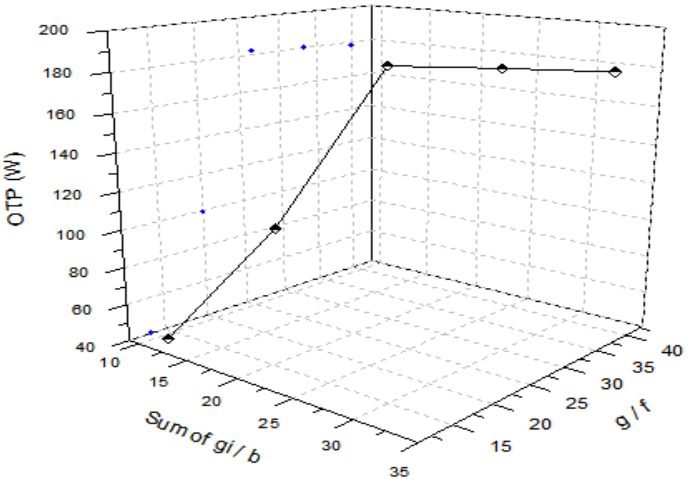
The receiver is an essential part of CSP plants. Thus, various studies investigated trapezoidal receivers dimensions in LFRs. [14] Investigated a receiver cavity that forms a V shape in LFR plant both experimentally and theoretically. Time, cavity width and the fluid and ambient temperatures are analyzed and optimized to enhance the efficiency. [15] Verified, with simplified ray-trace simulation, the number of receiver absorber tubes and the inclination of lateral walls in the cavity. Cavity depth and rock wool insulation thickness were optimized employing CFD. [16] Studied the influences of ambient temperature, absorber temperature, cavity depth, insulation thickness, inclination of side walls, glass window, and the emissivity of the selective absorption coating on the performance of the receiver. [17] Evaluated, by quantifying cavity heat transfer rate and heat loss, the Copper absorber tubes position. The effect of cavity angle has been studied by [18] by carrying out a CFD method for two cavity angles. [20] Analyzed the heat transfer rate and heat loss and evaluated, in different models, the cavity angle and of the tube size effects. The previous authors investigating on a trapezoidal cavity absorber for LFR didn't deal with cavity under vacuum.

The aim of the present study is to answer questions faced while designing plants similar to the studied one: What is the most advantageous mirrors width? What is the optimal distance between mirrors? What tube diameter to consider for absorbers? What is the optimal distance between absorber tubes? What is the most favorable position of absorber tubes according to the cavity depth? What velocity should HTF have?

3.2.1. Absorber tubes diameter effect

In order to evaluate the absorber tubes diameter effect on the OTP, dimension of the cavity kept unchanged while the absorber tubes diameter is changed. Two parameters are observed: sum of absorber tubes diameters (gi) / Cavity base width (b) and Absorber tube diameter (g) / Cavity depth (f). The effect of the two parameters is represented by a 3D representation in Fig.5 with an YZ projection in order to visualize and to correctly read the values of the OTP for each parameter.

Fig.5 reveals that a sum of absorber diameters that occupy 22% of the cavity base width gives a maximum value of the OTP (OTP= 182,06 W), and a diameter up to 26.6% of the cavity depth ensures also a maximum OTP. [20]



Analyzed the cavity angle and the tube size effects in a prototype trapezoidal cavity non under vacuum used in a LFR. It has been seen that increasing diameter tubes does not essentially result in a given variation in tube surfaces heat

Fig.5 The influence of Sum of gi/b and g/f on the OTP.

transfer rate, and the tube size is more influencing on cavity angle in comparison with heat transfer rate. Since the heat flux is the heat transfer rate per unit area and with a constant tube area, the heat transfer rate keeps the same variation as the heat flux. Unlike what was found by [20], in the case of non under vacuum cavity and according to the current study, the heat transfer rate forms a curve that increases by increasing tube diameter until reaching an optimal value, and it decreases.

3.2.2. Optimal distance between aborber tubes

Based on the optimal diameter of the cavity dimensions, considered (g= 40mm) the optimal distance between absorber tubes was studied by varying the latter while keeping the cavity dimensions and tubes diameter fixed. Two parameters were studied: Width occupied by absorber tubes (3d+g) / Cavity base width (b) and Sum of distances between absorber tubes (di) / Cavity base width (b). As can be seen from Fig.6 the OTP attain its maximum when (3d+g) / b is 32,13% and Sum of di / b is 26,66%. In other words, absorber tubes occupy 32.13% of cavity base width with a distance between tubes forming 26.66% of the same width.

Present results are unlike what was found by [4] where the pipes should be closer together to obtain lower heat loss then a better heat flux because the natural convective cooling between tubes is limited by the smaller gap. This difference is due to the difference between the two studies assumptions; indeed, in this study the cavity is considered under vacuum then losses caused by radiation became the major mechanism for heat transfer losses of the receiver. Forced convection also appeared, considering the HTF velocity. The insulation using a specific material is not studied.

3.2.3. Optimal position of the absorber tubes vis-a-vis the cavity depth

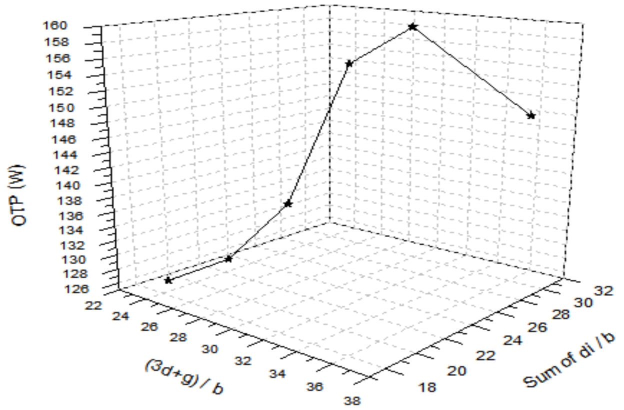


Fig.6 The influence of (3d+g)/ b and Sum of di/ b on the OTP.

This parameter allows positioning the absorber tubes according to the cavity depth. [4] Optimized an LFR non under vacuum cavity receiver so as to come up with the suitable geometry for minimizing heat losses and side wind load. In their article, it has been shown that the pipes should be closer together and bunched up against the top insulation to obtain lower heat loss. [30] also gave optimal non under vacuum cavity shape and tube bundle arrangement for maximizing plant optical efficiency, minimizing plant thermal heat loss and finding the economic optimization of the plant. It has been concluded that reducing cavity angle or rising cavity depth cause a decrease in the absorbed solar power throughout a day. The daily absorbed solar power increases while increasing the tube gap parameter. For a given tube gap, an increase in tube radius causes a decrease in the daily absorbed solar power. For a precise mounting altitude of the cavity, decreasing the mirror gap produces daily solar power increasing.

As indicated in Fig.7 the OTP is enhanced by approaching the absorber tubes from the middle of the cavity depth. The maximum is reached when the tubes are at the position 53% of the cavity.

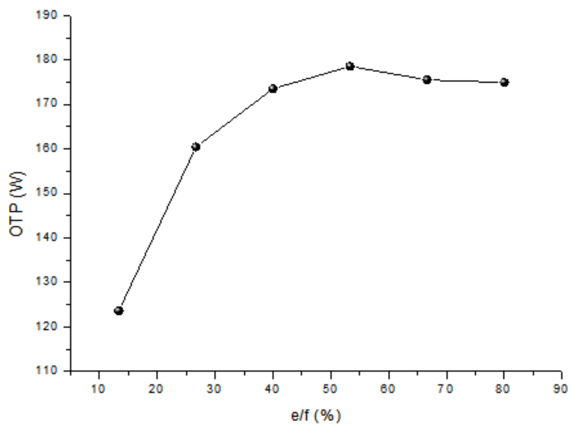


Fig.7 The relationship between Output Thermal Power of absorber tubes and Distance between the cavity top and

absorber tubes (e) / Distance between cavity top and cavity base (f).

[4] Concluded that the tubes should be bunched up against the top insulation to obtain better heat flux; in the current study, it has been found that absorber tubes should be in the middle of the cavity to maximize the OTP. As mentioned earlier, this difference is attributed to the difference between considered assumptions.

3.2.4. HTF velocity

HTF velocity plays a critical role in the performance of CSP plants since the fluid motion enhances heat transfer. Increasing velocity means increasing the flow turbulence. In this part, the ratio HTF velocity / absorber tubes length has been studied.

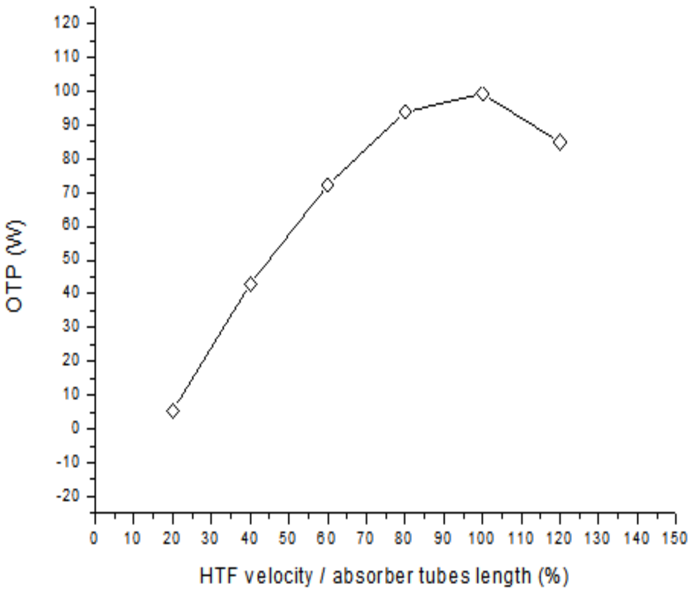


Fig.8 HTF velocity/ absorber tubes length influence on OTP.

As seen in Fig.8, OTP reaches its maximum when the fluid passes through the absorber tubes in one second although the outlet temperature decreases with increasing velocity, as shown in Table 3. Similar to [45] the outlet temperature of the HTF is found to be non-constant and non-uniform, but in the current study the outlet temperature is considered to be the HTF mean temperature at tubes outlet($\frac{T_{max}+T_{min}}{2}$). [45] numerically investigated the performances of the parabolic trough collector system using molten salt as HTF; it has been proved that the cross-section temperature difference decreases from 2 K to less than 1 K when the inlet velocity of the HTF changes from 1 m/s to 4 m/s. In other words, with the same inlet temperature, the outlet cross-section temperature decreases when the HTF velocity increases, which is identical to current obtained results. As can be concluded from Fig.9, radiation losses decrease with the increase of the HTF velocity thus with the decrease of the outlet absorber tubes temperature. This is why the OTP has kept its bell-shaped curve.

Table 3. Variation of the outlet absorber tubes temperature according to HTF velocity

HTF velocity (m/s)	Absorber tubes (from left to right)	Outlet temperature (K)
0,05	1	450
	2	425
	3	425
	4	553,5
0,1	1	425
	2	400
	3	400
	4	528,5
0,15	1	415
	2	387,5
	3	387,5
	4	515,5
0,2	1	412,5
	2	375
	3	375
	4	490
0,25	1	387,5
	2	350
	3	350
	4	489,5
0,3	1	381,5
	2	313
	3	313
	4	470,5

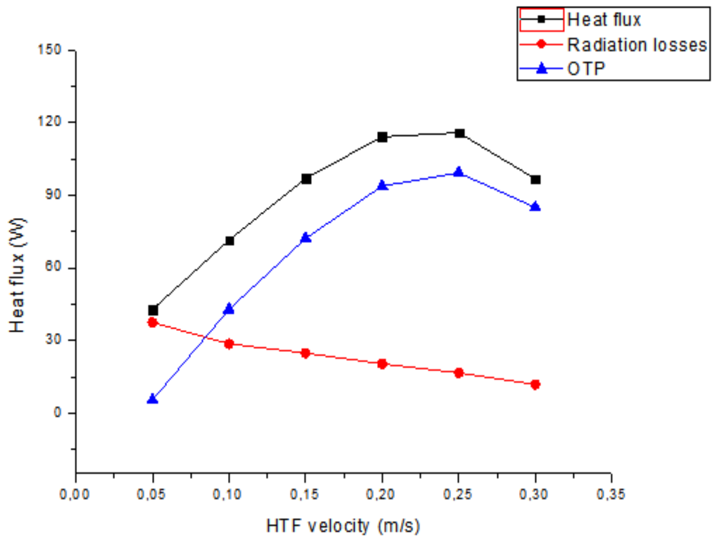


Fig.9 Heat flux, radiation losses and OTP variation in relation to HTF velocity.

4. Conclusion

The objective of the present research is to evaluate the effect of distance between Fresnel mirrors, absorber tubes diameter, distance between absorber tubes, their position according to cavity depth and HTF velocity in an under vacuum trapezoidal cavity absorber for linear Fresnel reflector. The following conclusions are drawn: the OTP attains its maximum when:

- Mirrors width/Distance between mirrors (%) reaches approximately 78%.
- A sum of absorber diameters that occupy 22% of the cavity base width and a diameter up to 26.6% of the cavity depth.
- Absorber tubes occupy 32.13% of cavity base width with a distance between tubes forming 26.66% of the same width.
- The tubes are at the position 53% of the cavity depth.
- The fluid passes through the absorber tubes in one second, although the outlet temperature decreases with increasing velocity.

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