Optical Modeling and Thermal Behavior of a Parabolic through Solar Collector in the Algerian Sahara

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Abstract

This study is concerned with transfer of solar energy to thermal energy by using a parabolic trough collector (PTC) in the Algerian Sahara region. The water used a heat transfer fluid. A mathematical model drawn from the energy balance equation was applied on the absorber tubes. Finite difference method was used to solve the non-linear system resulting from the numerical analysis of mathematical equations. Matlab was used as a programming language. This study was able to get the variation of the optical performance, the thermal efficiency, the outlet temperature of fluid, the temperature of the absorber tubes, the glass's temperature and the coefficient of thermal losses for the concentrator. With the results obtained, the thermal efficiencies had spent 80% to up to 82%, and outlet temperature fluid has exceeded 515k. The results obtained in this paper are an honorable and very encouraging for investment in this field of clean technology.

Key words

1. Introduction

Currently, the world eyes are heading towards the exploitation the all kinds of renewable energies (solar, hydraulic, biomass, wind, geothermal); these energies are clean and continuous [1]. The solar energy is the energy of the future, Algeria is the first country in Africa by area, and more than four-fifths of their territory is desert. Algeria has a very important solar energy source on part of its geographical situation. Annual solar radiation on almost all of the national territory

exceeds 2000 hours, where can reach the 3900 hours (high plateaus and Sahara). The solar energy potential received daily on a horizontal surface of 1 m² is of the order of 5 KWh over the major part of the national territory, where it find that the average energy received at the level of the coastal region is equal to 1700 [KWh/m²/year], 1900 [KWh/m²/year] to the Highlands and 2650 [KWh/m²/year] to the South of the country [1]. Figure (1) illustrated the monthly average of the overall radiation received on horizontal surfaces in the period between 1992 and 2002 on the national territory.
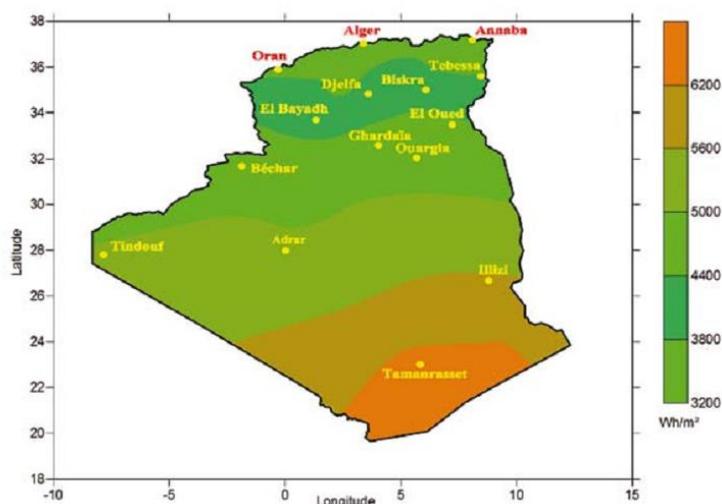

Fig.1. Average Monthly Global Irradiation Received on a Horizontal Surface, Period 1992-2002 [Wh/m²] [2].

In previou8s studies we have spoken to capture and exploitation of solar energy in the Algerian territory, in many fields [3-13]. This article will talk about the exploitation of solar energy by using the parabolic trough solar concentrator (PTC) to obtain the water steam with a very high temperature at site of Guemar, mandate of El-Oued, in country of Algeria. This technology is mature and very effective; it is available today in the Algeria (the powerhouse hybrid of Hassi R'mel and the solar village of Adrar). An energy balance was executed on absorber tube for assessment of the absorber tube temperature, the fluid temperature, the glass temperature and thermal loss coefficient, all this by using a numerical solution with the implicit finite differences method. This study was done using the actual data from the collector of Hassi R'mel, mandate of Laghouat, in country of Algeria. Matlab as a tool was used as tool for program language.

2. Parabolic Trough Solar Concentrator Description

The concentration principle of energy is important on our daily life. With the sun there is an enormous amount of potentially usable energy, and when it is concentrated, a mass of energy is much simpler to store, transform and move [14]. Even if there are exceptions, the access to high concentrations of energy allows in most cases to do just about what you want with a minimum quantity of power.

The parabolic trough solar concentrator has a copper tube on the cylindrical shape with a suitable selective layer located in the focal line of the parable. The selective surface that has a high absorption coefficient and a good absorbent of solar radiation, it has a high radiant emittance to Infrared waves [3-13]. The receiver tube is covered with a glass tube. The direct solar radiation is concentrated on the absorber tube by a mirror on the shape of a parabola. A fluid heat transfer (HTF) moving into the copper tube and absorbs the heat that will use in many areas of industrial or household [3-13].

The parabolic trough concentrator is the most promising technologies to take the place of non-renewable (fossil and nuclear energies) especially in the industrial field (power plants, hybrid systems, desalination, air conditioning, refrigeration, irrigation, etc.) [3-7, 15].

The parabolic trough solar concentrators are the most widely used in linear concentrators family for thermodynamic solar energy conversion, especially in industrial and domestic areas that require an operating temperature between 80 ° C and 160 ° C [4-6, 16], but the flat solar collectors are used for low and medium temperature applications [9].

The electricity production by new and renewable ways is the priority of all world [3-7, 9, 12, 17]. As it is known,, the electricity generation requires high temperatures between 400 ° C and 1200 ° C. the use of a parabolic trough solar collector that can produce electricity, it can be produce a superheated steam in power plants with parabolic trough concentrators, where the water steam temperature up to 1500 ° C and more [3-7, 15].

A central electric hybrid gas/solar was established by Algeria with German specifications in the region of Hassi R'mel (Laghouat). This central is focusing 25 MW of solar energy, on an area of 18000 m² by using the parabolic trough solar concentrator, in conjunction with a central to gas turbines with power equal to 130 MW [6, 18].

Tab.1. Geometric Characteristics of the Absorber Tubes.

geometric characteristics	Value
Outside diameter of the absorber ($D_{A,ext}$)	70 mm
Inner diameter of the absorber ($D_{A,int}$)	65 mm
Outside diameter of the glass ($D_{V,ext}$)	115 mm

Inner diameter of the glass ($D_{V,int}$)	109 mm
Mirror length (L)	12270 mm
width mirror (l)	11900 mm

Simulations will be on absorber tubes that they have the same dimensions and characteristics of the absorber tubes used in the central of Hassi R'Mel. Table (1) illustrated the geometric characteristics of the absorber tubes for 1 segment.

Six days of the year were chosen for this simulation, they are the typical days for the month: January, March, may, July, September and November for the year 2014. These measures are taken from the archive of Guemar station for meteorological measurements, which located in Guemar airport [19]. Table (2) illustrated the weather data for each day.

Tab.2. Weather Data for the Site of Guemar in the Six Typical Days

Month	Typical day	The maximum ambient temperature	The minimum ambient temperature	The average temperature of the room	Wind speed
January	17	19	8	14	calme
March	16	21	9	15	calme
May	15	28	17	22	calme
July	17	40	25	32	calme
September	15	42	25	34	calme
November	14	27	13	20	calme

3. Optical Modeling

This part will make it possible to estimate the influence of the concentration degree of the solar radiation on the conversion efficiency of the solar energy.

Tab.3. Optical Characteristics of Four Absorbers Tubes.

Parameter	Value
global average optical error ($\sigma_{optique}$)	03 mrad
Reflectance of mirror (ρ_m)	0,92
Transmissivity of the glass	0,945
Coefficient of absorptions of the absorber (α)	0,94
The emissivity of the absorber tube (ε_A)	0,12
The emissivity of the glass (ε_V)	0,935

Optical modeling was performed with the SolTrace software. SolTrace developed by the American laboratory NREL "National Renewable Energy Laboratory" [3-7, 12, 20]. The optical system of the solar concentrator is composed of two parts, the reflective surface and the absorber. The reflective surface modeled as a single mirror of parabolic shape. The four absorbent tubes are located at the center of the focal line of the concentrator to absorb the greatest possible quantity of solar energy. Table (3) shows the optical characteristics of four absorbers tubes.

The optical simulation allows estimating the flow and the incident heat concentration on the surface of the absorber. While the optical modeling, it takes into account:

- The value of solar radiation at every moment;
- The value of the incidence angle of solar radiation on the reflective mirror;
- The properties of each mirror (geometrically and optically);
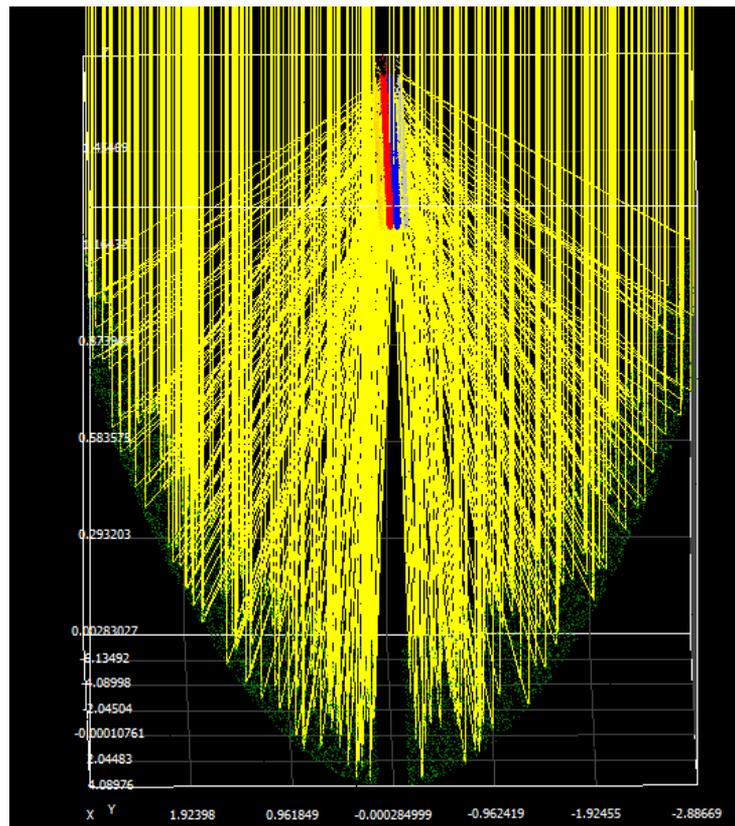- The properties of the absorber tubes (geometrically and optically).

Figures (2a-c) represents the schema of parabolic trough concentrator with the SolTrace software.

Where figure (2a) shows the sigle stage test; figure (2b) illustres the single stage test with 300 sun rays and figure (2c) presentes the final intersections only of the single stage test.
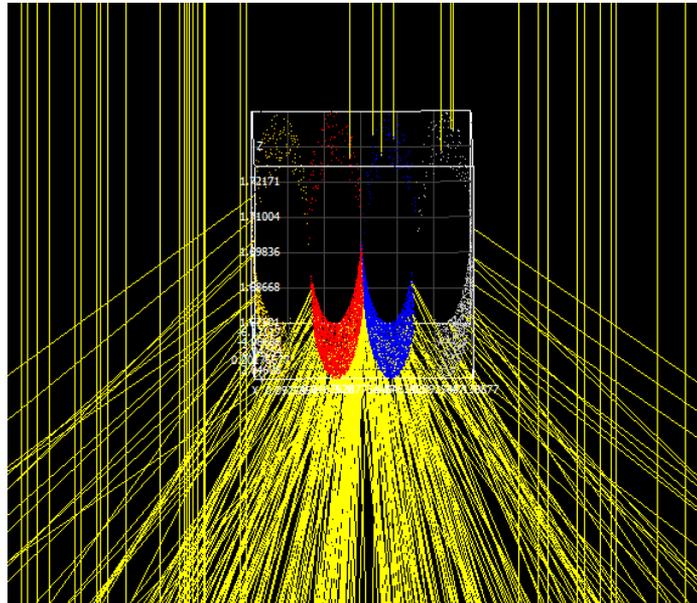
The optical properties are uniform on the whole of the reflecting surface. The solar monitoring is considered to be very accurate; with the opening of the concentrator is always perpendicular to the rays from the Sun's disk.
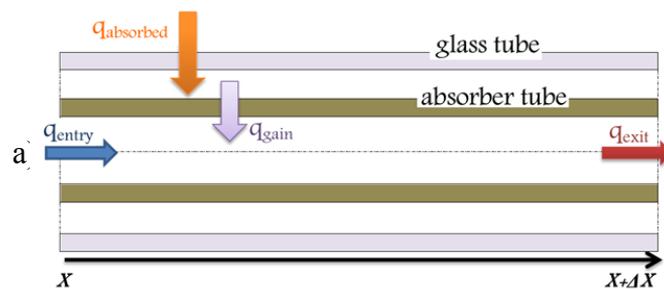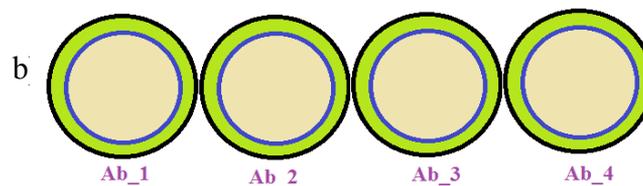
(a)

(b)

(c)

Fig.2. Parabolic Trough Concentrator Scheme with the SolTrace Software.

4. Thermal Behavior

The parabolic trough concentrator was analyzing it thermally by a numerical tool, this modeling is used to estimate the variation of the temperature of the heat transfer fluid (water) on basis of a direct solar radiation (DNI) in site of Guemar (altitude 61 meters, latitude 33,51 ° N and longitude 6.78 ° E). The municipality of Guemar located in the state of El-Oued, Algeria. Guemar have a desert climate, dry winters and hot summers.
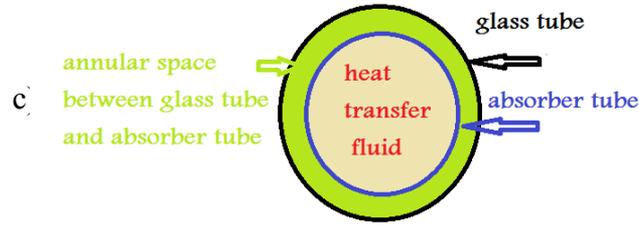
Fig.3. Heat Balance on a Segment of Parabolic Trough Concentrator [6]

The heat exchange occurs between the three elements: the heat transfer fluid, the absorber tubes and the glass tubes. Modeling of temperature is based on the energy balances characterized by the differential equations of three temperatures: TF (fluid), TV (glass) and TA (absorber tube). These equations vary during the illumination time (t) to the segment absorber length (x). The discretization of the finite difference method was chosen for solving the thermal system of nonlinear equations of assessments at the level of the absorber tube. A calculation by Matlab program was developed after the discretization of the equations. For the calculation of energy balance was asked as assumptions:

- The fluid flow is incompressible;
- The form of parabola is symmetric;
- The ambient temperature around the concentrator is uniform;
- The effect of the shadow of the absorber tubes on the mirror is negligible;
- The solar flux at the level of the absorber is evenly distributed;
- The glass is seen as opaque to infrared radiation;
- Exchange by conduction in the absorber and the glass are negligible.

4.1 Energy Balance for the Fluid

The energy balance for the fluid flowing through the absorber tubes is expressed by the following relationship [3, 4, 6]:

$$
\rho_F . C_F . A_{A,int} . \frac{\partial T_F(X,t)}{\partial t} = q_{utile} \\
- \rho_F . C_F . Q_v . \frac{\partial T_F(X,t)}{\partial X}
\tag{1}
$$

where ρ_F is the density of the fluid (kg.m^{-3}) ; C_F is the specific heat of the fluid (J.kg^{-1}.k^{-1}); $A_{A,int}$ is the inner surface of the absorber (m²) ; Q_v is the volume flow rate of the heat transfer fluid in

the absorber tube (m^3.s); q_{utile} is the quantity of heat exchanged by convection between the absorber and the fluid (W).

Boundary conditions and initial conditions of the eq. 1 are [3, 4, 6]:

$$T_F(0,t) = T_{F,entry}(t) = T_{amb}(t)$$
$$T_F(X,t) = T_{F,initial}(t) = T_{amb}(0)$$

$$(2)$$

All the thermo-physiques characteristics of water are based on its temperature.

4.2 Energy Balance for the Absorber Tube

The energy balance for the absorber is given by the eq. (3) [3, 4, 6].

$$\rho_A . C_A . A_A . \frac{\partial T_F(X,t)}{\partial t} = q_{absorbed}(t) - q_{exit}(X,t) - q_{gain}(X,t)$$

$$(3)$$

With ρ_A is the density of the absorber tube ($kg.m^{-3}$) ; C_A is the specific heat of the absorber tube ($J.kg^{-1}.k^{-1}$); A_A is the difference between the inner and the outer surface of the absorber tube (m^2); $q_{absorbed}$ is the quantity of heat absorbed by the absorber tube (W) ; q_{exit} is the amount of heat from fluid when it came out of tube (W).

The initial conditions of the eq. (3) are [3, 4, 6]:

$$T_A(X,t) = T_{A,initial}(t) = T_{amb}(0)$$

$$(4)$$

4.3 Energy Balance of the Glass Tube

In the same way, the energy balance for the glass is given by [3, 4, 6] :

$$\rho_V . C_V . A_V . \frac{\partial T_V(X,t)}{\partial t} = q_{int}(X,t) - q_{ext}(X,t)$$

$$(5)$$

where ρ_V is the density of the glass ($kg.m^{-3}$) ; C_A is the specific heat of glass ($J.kg^{-1}.k^{-1}$); A_v is the difference between the inner and the outer surface of the glass (m^2) ; q_{int} is the internal power

(convection and radiation) between absorber and glass (W) ; q_{ext} is the external power (convection and radiation) between glass and the atmosphere (W).

Eq. 6 is the initial conditions of the eq. 5 [3, 4, 6]:

$$T_V(X, t) = T_{V,initial}(t) = T_{amb}(0) \tag{6}$$

The thermal power emitted by the sun and received by the concentrator is therefore worth [3, 4, 6, 21]:

$$q_{absorbed} = \alpha.\rho_m.\gamma.A_c.K.DNI \tag{7}$$

With A_c is the surface of opening of collector (m^2); ρ_m is the mirror reflectance factor; K is the incidence angle correction factor; α is the coefficient of absorption of the absorber; γ is the factor of interception.

It can express the optical efficiency (η_{opt}) of the concentrator by [3, 4, 6, 22].

$$\eta_{opt} = \alpha.\rho_m.\gamma.K \tag{8}$$

The thermal efficiency (η) is given by the eq. 9 [3, 4, 6, 22]:

$$\eta = \eta_{opt} - \frac{U_L.A_A.(T_A - T_{amb})}{DNI \times A_C} \tag{9}$$

U_L is the coefficient of heat loss (W/m².K); T_{amb} is the ambient temperature (K).

4.4 Heat Loss Coefficient

The coefficient of heat loss (U_L) is expressed by [3, 4, 6]

$$U_L = \left(\frac{1}{C_1 \left[\frac{T_A - T_{amb}}{1+f} \right]^{0,25}} + \frac{D_{A,int}}{D_{A,ext} \times h_v} + \left(\frac{\sigma(T_A^2 + T_{amb}^2).(T_A + T_{amb})}{[A_1]^{-1} - [A_2]} \right) \right)^{-1} \tag{10}$$

With,

$$A_1 = \varepsilon_A - 0,04(1 - \varepsilon_A)\left(\frac{T_A}{450}\right)$$

$$A_2 = \left(\frac{D_{A,int}}{D_{A,ext}}\right)\left(\frac{1}{\varepsilon_V}\right)\left(\frac{f}{\varepsilon_V}\right)$$

(11)

where ε_A is the emissivity of the absorber tube; ε_V is the emissivity of the transparent glass envelope; σ is Stefan-Boltzmann constant ($\sigma = 5,670 \cdot 10^{-8}$ W.m^{-2}.K^{-4}).

The factor (f) takes into account the loss coefficient of wind and which can be obtained by the following [3, 4, 6]:

$$f = D_{A,int}^{-0,4}(1,61 + 1,3\varepsilon_A)h_v^{-0,9} \times$$

$$\exp[0,00325(T_A - 273)]$$

(12)

C_1 is given by the following empirical expression [3, 4, 6]:

$$C_1 = \frac{1,45 + 0,96(\varepsilon_A - 0,5)^2}{D_{A,int}\left(\dfrac{1}{D_{A,int}^{0,6} - D_{A,ext}^{0,6}}\right)^{1,25}}$$

(13)

The term h_v is the wind convection coefficient, it can be obtained by the following equation (according to McAdams (1954)) [23, 24]:

$$h_v = 5,7 + 3,8V$$

(14)

V is the speed of the wind, (m.s^{-1}).

Therefore, there are three unknowns (T_F, T_A and T_V). To resolve system reformulates of all relations, it will be adapted the following matrix form:

[The coefficient matrix] x [the vector of unknowns T_F, T_A and T_V] = [vector of the second member]

where, the vector of the second member is not null.

5. Analysis of the Results

The results obtained on the six days are well explained below. The normal solar radiation (DNI) is focused and concentrated on the absorber tubes. To calculate the direct solar radiation from sunrise to the sunset, an algorithm was developed that simulates the direct solar radiation by the semi-empirical model of PERRIN DE BRICHAMBAUT [8, 13]. Figure 4 illustrates the variation of direct solar radiation during the six days in function the time.
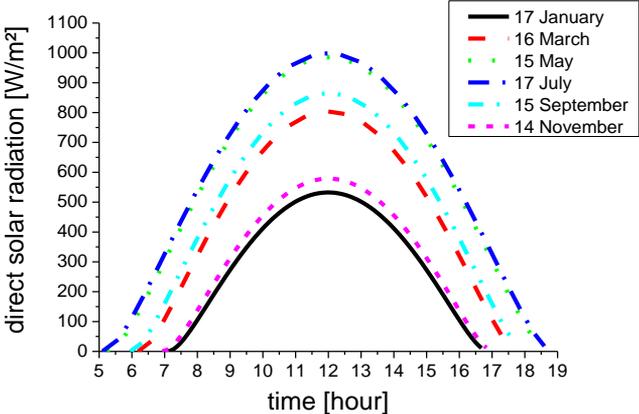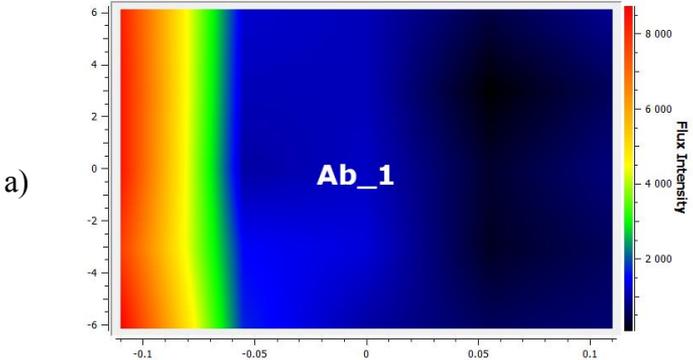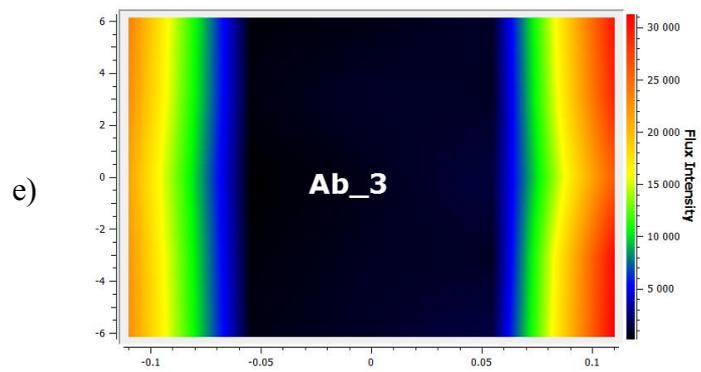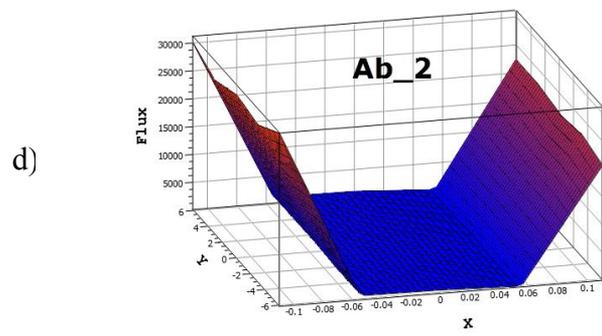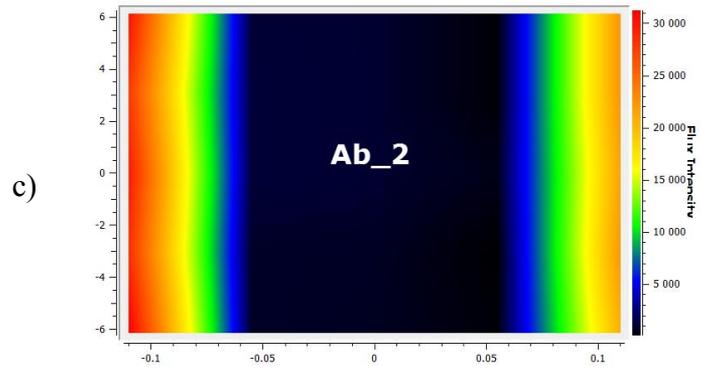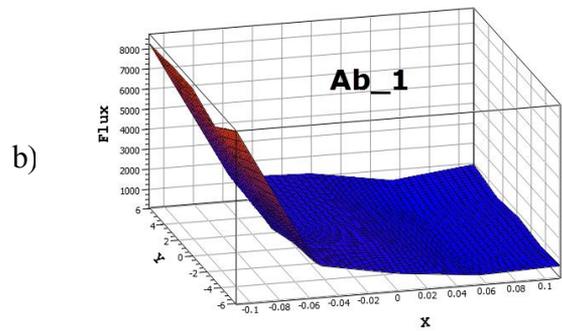

Fig.4. Evolution of Direct Solar Radiation in Function of Time.

It notes that in July 17th, 2014 the direct solar radiation is maximum at the true solar noon which it can reach to 1000 [w/m²].

The main objective of the optical modeling is know the concentration power of our collector, and the evolution of the heat flux on the level of the absorber tubes, this evolution was based on the variation of incidence angle ray of sunshine. Figures (5a-h) present the contour of the average heat flux intensity with a value of direct solar radiation equal to 1000 [W/m²].
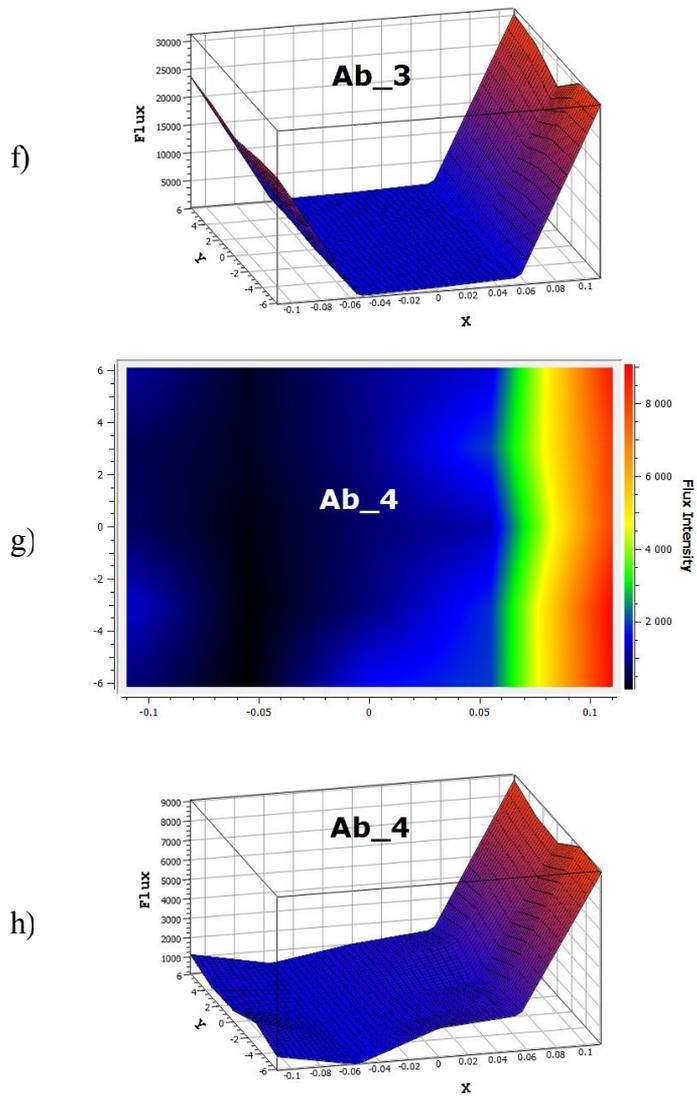
a)

b)

c)

d)

e)

f)

g)

h)

Fig.5. The Contour of the Average Heat Flux Intensity with a Value of Direct Solar Radiation Equal 1000 [W/m²]

Figure 6 illustrates the thermal evolution of thermal efficiencies for six days.
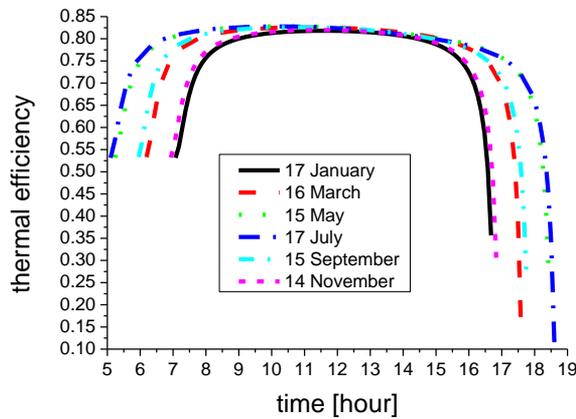
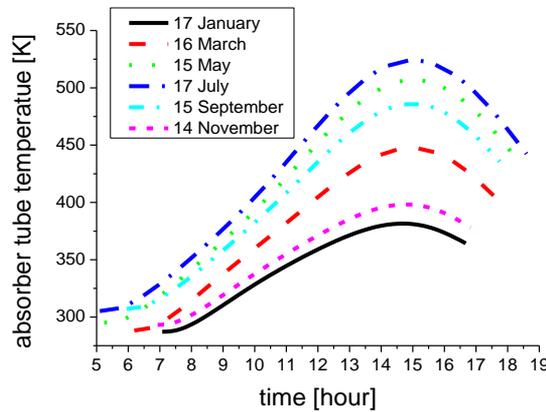Fig.6. Evolution of Thermal Efficiencies According the Time.

Fig.7. Evolution of Absorber Tube Temperature Versus Time.

Based on the Figure 6, it can say that the concentrator gave a good performance. The optical efficiency of the collector is higher than 84%.   For the thermal efficiency, it note that the performance decreases after the maximum value (82%), because:

- Water temperature at inlet of absorber tubes is almost identical to the ambient temperature, thus corresponding to perfect thermal insulation and lower heat loss to the atmosphere;

- The thermal losses who believe with increasing water temperatures respectively at the entrance and at the outlet of the absorber tubes of the collector.

Therefore, the thermal efficiency is connected with the permissible thermal resistance and the thermal inertia of the construction materials of the absorber tubes. Thus, the solar radiation concentration by the mirror parabolic trough has a very significant effect on thermal performance.

Figure (7) represents the variation of absorber tube temperature, notes that paces vary similarly, the only difference at the level of the curves slopes.

Tap water was used as heat transfer fluid with a flow equal to 0.015 Kg.s^{-1}. The role of the heat transfer fluid is carrying the heat from the source to use. Water has a high heat capacity, is not polluting the environment. Figure 8 represents the evaluation of the fluid temperature at the outlet of tube absorber according to true solar time.

The water turns into steam at temperature up to 250 ° C or more. The fluid temperature at the outlet of the absorber tubes is inversely proportional to the direct solar radiation, and it depends mainly on the $q_{absorbed}$ (t), which is based on optical parameters, concentrator geometrical and climatic conditions.

Figure 9 below illustrates the evolution of the glass temperature versus true solar time.

According to the figures 7-9, the highest temperature is the temperature of absorber tubes, then the fluid temperature and finally the glass temperature. The results are very logical with the sequence of the energy exchanges at the level of the absorber tube. A great quantity of energy absorbed by the fluid, and a small quantity goes in the form of heat loss. Figure (10) represents the evolution of the coefficient of heat loss based on the difference in the temperature between the absorber tube and the ambient temperature.

It observed that the loss increases with the increase of the temperature of the absorber tubes, therefore the absorber is the seat of heat loss, the creation of vacuum between the absorber tubes and glass tubes could significantly reduce the losses by convection. The glass is transparent to visible solar radiation, but opaque to infrared (IR); thus it covers the absorber tubes by a glass tube, so with this technique, the radiation losses by infra-red emission is greatly reduced.
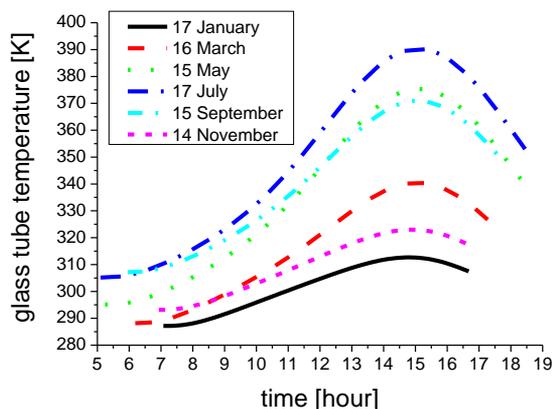

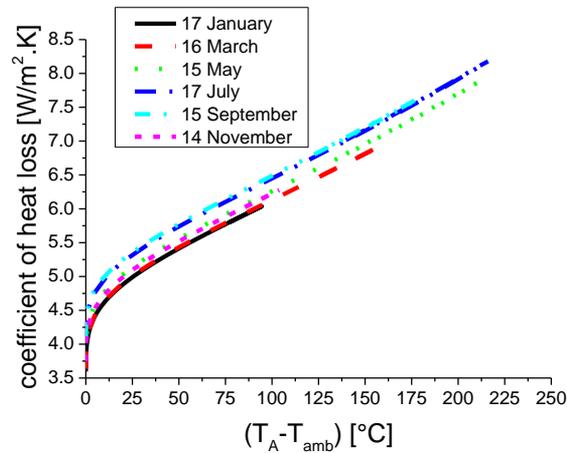Fig.8. Evolution of the Glass Tube Temperatures According to the Time.

Fig.9. Evolution of the overall Coefficient of Heat Loss on the Basis of (T_A-T_{amb}).

Conclusion

Algeria is the largest country in Africa; it's counted among the sunniest countries in the world. Algeria relies essentially on the two fossil sources (gas and oil) in its own production of electrical energy. Because of the rapid development of renewable energy technology in recent years, Algeria is looking for other inexhaustible sources and friendly to the environment. Currently in this country, the search for new energy sources is a priority and a duty thing. The parabolic trough collector is a simplified model of linear solar concentrator, it's very effective. In this paper, a model of parabolic trough solar concentrator was studied, where the semi empirical model of PERRIN DE BRICHAMBAUT was used of a direct solar radiation simulation. The results were represented for six typical days for the year 2014 at Guemar region, state of El Oued, Algeria. This study examines the different modes of heat transfer at the level of absorber tubes. The concentrator consists of a semi-cylindrical mirror and four horizontal absorber tubes. The solar rays focused on the horizontal tubes, which circulates a heat transfer fluid (water) which will be used to transport the heat to the points of use according to the needs. According to the results, the temperature of the fluid at the outlet of the absorbers tubes can reach 250 ° C or more. It can say that the parabolic trough concentrator is the most preferred collector for the production of steam at high temperatures that can be obtained without alteration of collector performance. this numerical study shows that the fluid temperature exceeds the threshold of 518 [K] for the summer period; even in winter the temperature remains more or less good, it reaches 345 [K]. These results are very encouraging for the exploitation of this type of concentrator.

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Nomenclature

A_A	The difference between the inner and the outer surface of the absorber tube, m²
$A_{A,int}$	The inner surface of the absorber (m²)

A_c	The surface of opening of collector, m²
A_v	The difference between the inner and the outer surface of the glass, m²
C_A	The specific heat of the absorber tube, J.kg.$^{-1}$ k^{-1}
C_A	The specific heat of glass, J.kg^{-1} .k^{-1}
C_F	The specific heat of the fluid, J.kg^{-1} .k^{-1}
$D_{A,ext}$	The outside diameter of the absorber, m
$D_{A,int}$	The inner diameter of the absorber, m
DNI	The Direct sunlight, W.m²
$D_{V,ext}$	The outside diameter of the glass, m
$D_{V,int}$	The inner diameter of the glass, m
f	A factor takes into account the loss coefficient of wind
h_v	The wind convection coefficient, W.m^{-2}.K^{-1}
K	The incidence angle correction factor
L	The mirror length, m
l	The width mirror, m
$q_{absorbed}$	The quantity of heat absorbed by the absorber tube, W
q_{exit}	The amount of heat from fluid when it came out of tube, W
q_{ext}	The external power (convection and radiation) between glass and the atmosphere, W
q_{int}	The internal power (convection and radiation) between absorber and glass, W
q_{utile}	The quantity of heat exchanged by convection between the absorber and the fluid, W

	The volume flow rate of the heat transfer fluid in the absorber tube, $m^3.s^{-1}$
Q_v	
T_{amb}	The ambient temperature, K
U_L	The coefficient of heat loss, $W.m^{-2}.K^{-1}$
V	The wind velocity, m

Greek Symbols

γ	The factor of interception
α	The coefficient of absorptions of the absorber
ε_A	The emissivity of the absorber tube
ε_V	The emissivity of the glass
η	The thermal efficiency
η_{opt}	The optical efficiency
ρ_A	The density of the absorber tube, $kg.m^{-3}$
ρ_F	The density of the fluid, $kg.m^{-3}$
ρ_m	The Reflectance of mirror
ρ_V	The density of the glass, $kg.m^{-3}$
σ	The constant of Stefan-Boltzmann, $W/m^{-2}.K^{-4}$
$\sigma_{optique}$	The global average optical error