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Thermal Analysis and Modeling of a Parabolic Concentrator with Two Thermal Receivers at the Focal Point

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ABSTRACT

The parabolic solar concentration technique is the most efficient of all thermodynamic solar energy production techniques. This ranking is due to its high thermal efficiency. Unfortunately, it is the least used because of the difficulties of storing its energy. In order to meet the challenge of intermittency that plagues the use of this technique. Our work focuses on the coupling of a parabolic concentrator with two receivers at focal point. These two receivers are a boiler and a Stirling engine. We modeled the two receivers, evaluate the power received and concentrated by the concentrator and the temperature of the receiver for a fixed direct radiation. Thus, with a concentrator of 15 m^2 and the radiation measured for the day of 30_10_21, the concentrated thermal power is around 10kW from 10am to 4pm. With a radiation of 900 W. m^{-2} the receiver can be brought from 30°C to 800°C in 300 seconds (s) for the same surface of the concentrator. With the defined thermal power, the Stirling engine thermal receiver can be raised from 30°C to about 631°C in 120 s and the boiler to about 563°C in 180 s. This study proves the possibility of coupling two receivers to a parabolic concentrator.

INTRODUCTION

The countries of the Sahel are countries with enormous solar potential [1, 2]. Although they have a lot of solar potential, they are part of the countries in the world that have a very low electrification rate of about 10 %, for example in Niger. In this country, which is fifth among the sunniest countries in the world, about 73.8 % of the electricity consumed comes from the neighboring country, Nigeria [2]. The country's electrification rate falls to 3.14 % in rural areas, where 80.7 % of its population resides. This low rate of electrification of rural areas is due to the high cost of transporting electricity to these areas and the insufficient production. Hence the interest in electrifying them with efficient systems that can be adapted to isolated sites.

Exploitation of solar radiation for the production of electrical energy: two different ways [3]:

- the photovoltaic technique whose electrical yield varies from 9 to 20 % [3, 5];
- the thermodynamic solar technique whose electrical efficiency varies from 14 to 50 % [6, 10].

In this work we are interested in the last technique which consists in producing electricity by concentrating the solar radiation towards a focal point.

Among all the solar concentration technologies, the concentration technique using a parabolic reflector remains the best because of its high thermal efficiency (about 68 %) and is adaptable to isolated locations [6, 11, 12]. Unfortunately, it is the least mature because of the difficulties related to the storage of its energy [13, 14]. This study is devoted to the thermal analysis and modeling of the two receivers at the focal point of a parabolic concentrator. These receivers consist of a boiler and a Stirling engine.

The general objective of this study is to establish a model of the evolution of the thermal power at a parabolic concentrator with two receivers.

The specific objectives are presented in Table 1.

Table 1 The specific objectives

The specific objectives are:	Establish the thermal model of the two receivers;
	Evaluate the solar power received by the reflector;
	Evaluate the concentrated solar power;
	Evaluate the temperature generated by this concentrated thermal power.

MATERIALS AND METHODS

The study focuses on the thermal analysis and modeling of the usable thermal power at the two receivers of the focal point of a parabolic concentrator: The boiler and Stirling engine.

The system consists of the reflector, the boiler and the Stirling engine.

Figure (1) shows the schematic model of the system; from the reflector, to the receivers. The heat concentrated on the surface of the receiver is transferred by conduction to the receiver and then to the thermal fluid boiler and the receiving tube of the Stirling engine. The heat is then transferred from the heat transfer fluid on the inner wall of the receiver to the permanent heat transfer fluid, which in turn transfers the heat it has stored to the coil tube by convection. Heat will be transferred by conduction from the outer wall in contact with the permanent fluid to the inner wall in contact with the heat transfer fluid. In the serpentine tube, the heat is transmitted by conduction from the inner wall of the tube to the heat transfer fluid. Once heated to a defined temperature, the heat transfer fluid is expelled to the thermal storage tank where it will be discharged by exchanging its heat with the materials in the thermal storage tank which will store the thermal power of the fluid [15]. At the same time, heat is transferred from the receiver to the working gas of the Stirling engine which will produce mechanical work and the latter will produce electricity.

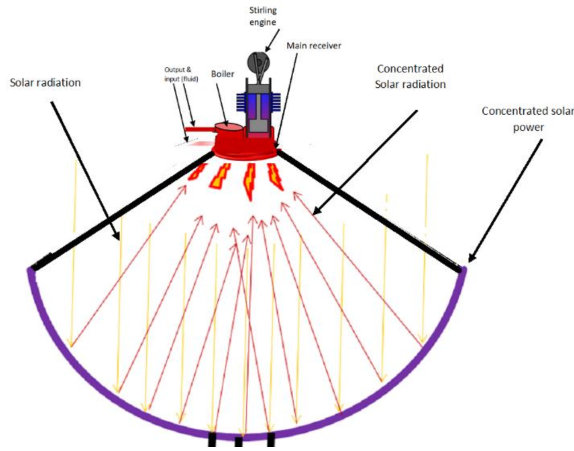

Figure 1 Dual receiver concentration system model

The boiler has a capacity of 2 liters of thermal fluid. This fluid will be heated to a temperature requiring a thermal power of 4 kW. The thermal fluid which is heated through this boiler, will be transferred to the thermal battery.

The material of the boiler considered in this work is aluminum. The boiler has a mass of 1.5 kg and specific heat is 900 J. kg^{-1}. $°C^{-1}$.

The Stirling engine has a thermal power of 5 kW. The latter is the power required for this type of Stirling engine to produce an electrical power of 3 kW [16].

The thermal receiver tube of the Stirling engine is made of copper. The specific heat is 380 J. kg^{-1}. $°C^{-1}$ we suppose a mass of 2.5 kg.

The total mass at the focus of the concentrator will be 4kg and the main receiving material is aluminum of specific heat of 900 J. kg^{-1}. $°C^{-1}$.

The heat losses are integrated according to the values found in the literature are presented in Table 2:

Table 2 Heat losses

Parameter	Losses (%)
Convection losses at the boiler	0.20 % of the thermal energy received [17] ;
Radiation losses are	0.5 to 2 % [18,19] ;
The losses of the boiler	5 % [20] ;
Conduction losses of the cylinder wall are	5 % [21]

The direct radiation data used in this work were measured on the roof of the Physics Department of the Faculty of Science and Technology. Longitude: 2.09°; Latitude: 13.50°.

We considered a concentrator with an opening area S_{cp} of 15 m² the concentrator has a reflection coefficient of $\rho = 0.97$, the proportion of interception is $\gamma = 0.8$, the receiver's absorption coefficient $\alpha = 0.9$, transmittance of air $\tau = 0.98$.

Thermal analysis of dual receiver system

The amount of heat received by a receiver at the focal point of the concentrator is obtained from the energy balance equation. It describes the theory of many aspects of the concentrator and the receiver[22, 23, 15, 24].

In this study, we consider that the temperature distribution inside solid or liquid materials is uniform and that these materials have high thermal conductivity.

Figure (2) shows the schematic model of the two receivers of the thermal energy concentrated by the reflective surface of the parabola. In this diagram:

Q_{rec} : amount of heat from the concentrator; Q_u : power amount of heat usable by both receivers; Q_{f2} : amount of heat received heat transfer fluid; Q_{fs} : amount of heat received by the gas from the work of the Stirling engine; Q_{prc}: heat losses from the heat transfer between the permanent thermal fluid of the boiler and the heat transfer fluid of the coil tube;

Q_{pse} : heat losses related to the transfer from the receiver to the Stirling engine tube and from the tube to the thermal fluid of the Stirling engine work;

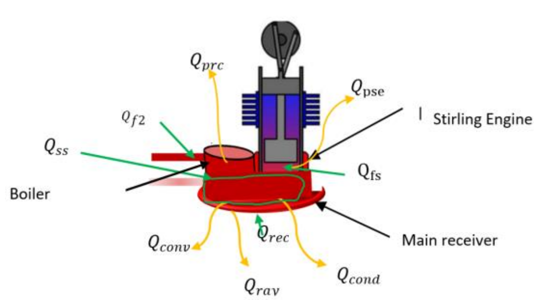

Figure 2 Receiver schematic model

Thermal power Q_{u1}, usable by a receiver placed at the focus of a parabolic concentrator is expressed by the expression (1).

$$Q_{u1} = Q_{rec} - Q_{P1} \quad (1)$$

The parameter Q_{P1} represents the power lost through the different modes of heat transfer at the receiver and Q_{rec} is the power received by the receiver. The power Q_{rec} expressed as a function of the various optical parameters, the geometry of the concentrator, and the material of the receiver is given by the equation (2).

$$Q_{rec} = Q_{cp}(\rho\gamma\alpha\tau) \quad (2)$$

Q_{cp} expressed in (3) is the power of solar radiation received by the opening of the concentrator [25,26,23] :

$$Q_{cp} = I_{bn} \times S_{cp} \quad (3)$$

S_{cp} is the aperture area of the concentrator and I_{bn} is the direct radiation from the Sun.

For our system where we have a double receiver (boiler and Stirling engine) we must integrate in the expression of Q_{rec} the thermal absorption coefficient of these two receivers the expression (2) becomes (4):

$$Q_{rec} = I_{bn} \times S_{cp}\left(\rho\gamma\alpha_{(s-r)t}\tau\right) \quad (4)$$

$\alpha_{(s-r)t}$ represents the total absorption coefficient of the receiver which is defined as a function of the absorption coefficient of the Stirling engine by α_{se} and the absorption coefficient of the boiler α_{rc} expressed in (5).

$$\alpha_{(s\_r)t} = \alpha_{se} + \alpha_{rc} \quad (5)$$

Once reflected by the concentrator, the solar rays that arrive on the receiver raise its temperature. It is initially at room temperature. Thus, the variation of this temperature generates heat losses related to the transfer by convection, by radiation and by conduction. The power lost during this process Q_{P1} is expressed in (6) [27, 28, 29, 30, 31, 32]

$$Q_{P1} = Q_{conv} + Q_{cond} + Q_{ray} \tag{6}$$

- the general formula Q_{conv} of the power lost by convective transfer is expressed by the equation (7) [33].

$$Q_{conv} = h_{conv} S_{rec} (T_{réc} - T_{amb}) \tag{7}$$

In the case of the two receivers, the thermal power $Q_{conv_{rec}}$ lost in the transfer related to the convection of the air with the receiver is expressed by the expression (8):

$$Q_{conv_{rec}} = h_{cv_{r\_air}} S_{rec} (T_{réc} - T_{amb}) \tag{8}$$

Avec : $h_{cv_{r\_air}} = h_{cv_{r\_se}} + h_{cv_{r\_rc}}$ (9)

With S_{rec} the surface of the receiver, $h_{cv_{r\_se}}$ the convection transfer coefficient between the receiver and the Stirling engine and $h_{cv_{r\_rc}}$ the convection transfer coefficient between the receiver and the boiler.

- Q_{cond} is the thermal power related to the transfer by conduction in which $\lambda_{réc}$ represents the thermal conductivity of the receiver and e is the thickness of the wall of the receiver, this power is expressed in the general formula (10).

$$Q_{cond} = \frac{\lambda_{réc} A_{rec}}{e} (T_{réc} - T_{amb}) \tag{10}$$

For the double receiver system that we propose, this thermal power related to the transfer by conduction is expressed in (11) by:

$$Q_{cond_{rec}} = \left(\frac{\lambda_{r-se} \frac{A_{rse}}{A_{rec}}}{e_{r-se}} + \frac{\lambda_{r-rc} \frac{A_{rrc}}{A_{rec}}}{e_{r-rc}} \right) (T_{réc} - T_{amb}) \tag{11}$$

e_{r-se}, λ_{r-se} et e_{r-rf}, λ_{r-rf} represents respectively the wall thickness, conductivity between the receiver and the Stirling engine and between the receiver and the boiler.

- Q_{ray} represents the power lost during the radiation transfer of the receiver expressed by equation (12) where ε is the emissivity of the receiver and σ is the Stefan-Boltzmann constant [33][32].

$$Q_{ray} = \varepsilon\sigma A_{rec}(T_{réc}^4 - T_{ciel}^4) \quad (12)$$

The power related to the radiation transfer for both receivers is expressed in (13):

$$Q_{ray_{rec}} = \left(\varepsilon_{se}\frac{A_{rse}}{A_{rec}} + \varepsilon_{rc}\frac{A_{rrc}}{A_{rec}}\right)\sigma(T_{réc}^4 - T_{sky}^4) \quad (13)$$

The temperature of the sky $T_{sky}$is calculated from the ambient temperature by applying the relationship illustrated in [26][1] expressed as (14) :

$$T_{sky} = 0{,}0552T_{amb}^{1{,}5} \quad (14)$$

The power lost by radiation by the pair of receivers is expressed by the formula (15).

$$Q_{ray_{rec}} = \left(\varepsilon_{se}\frac{A_{rse}}{A_{rec}} + \varepsilon_{rc}\frac{A_{rrc}}{A_{rec}}\right)\sigma(T_{réc}^4 - (0{,}0552T_{amb})^4) \quad (15)$$

The total thermal power lost during the heat transfer to this double receiving system at the focal point of the concentrator defined by equation (6), becomes (16):

$$Q_{P1} = \left[\left(\left(h_{cv_{r\_air}}A_{rec}\right) + \left(\frac{\lambda_{r-se}\frac{A_{rse}}{A_{rec}}}{e_{r-se}} + \frac{\lambda_{r-rc}\frac{A_{rrc}}{A_{rec}}}{e_{r-rc}}\right)\right)(T_{réc} - T_{amb}) + \left(\varepsilon_{se}\frac{A_{rse}}{A_{rec}} + \varepsilon_{rc}\frac{A_{rrc}}{A_{rec}}\right)\sigma(T_{réc}^4 - (0{,}0552T_{amb})^4)\right] \quad (16)$$

The quantity of heat Q_{ss} usable to the thermal fluid of the two sub-receivers is expressed by:

$$Q_{ss} = Q_{fs} + Q_{f2} \quad (21)$$

The energy balance of the global system will then be:

$$Q_{ss} = Q_{rec} - Q_{PG} \quad (22)$$

The amount of heat lost Q_{PG} by the overall system expressed as:

$$Q_{PG} = Q_{P1} + Q_{P2} \quad (23)$$

The heat balance becomes:

$$Q_{ss} = I_{bn} \times A_{app} \rho \gamma \alpha_{(s_r)t} \tau - Q_{P1} - Q_{P2} \quad (24)$$

Q_{P2}: thermal power lost during heat transfer to two receiving systems expressed in (25).

$$Q_{P2} = Q_{pse} + Q_{Prc} \quad (25)$$

The global thermal balance of the system is:

$$Q_{ss} = I_{bn} \times A_{app} \rho \gamma \alpha_{(s_r)t} \tau - h_{cv_{cd}} A_{rec} (T_{réc} - T_{amb}) - (\varepsilon_{tot}) \sigma A_{rec} (T_{réc}^4 - T_{ciel}^4) - \frac{\lambda_{rse-rsi} A_{rs}}{e_{rse-rsi}} (T_{réc} - T_{amb}) - h_{fse-t} A_{rs} (T_{réc} - T_{fse}) - h_{cf} A_c (T_{réc} - T_{amb}) - h_{f1-t} A_t (T_{réc} - T_{f1}) - \frac{\lambda_t A_t}{e_t} (T_{f1} - T_{f2}) - h_{t-f2} A_t (T_t - T_{f2})$$

(26)

In this work we have neglected the convection losses at the receiver and the heat exchange between the Stirling engine absorber and the boiler.

The thermal power absorbed by a boiler is expressed by [19] :

$$Q_{ch} = m_{ch} \cdot c_{pch} (T_c - T_{amb}) / t \quad (27)$$

m_{ch} : boiler mass;

c_{pch} : specific heat of the boiler;

T_c : hot temperature;

T_{amb} : ambient temperature;

t : is the time.

The thermal power absorbed by the receiver of a Stirling engine is evaluated by [28] :

$$Q_{rs} = m_{rms} c_{v_{rms}} (T_c - T_{amb})/t \quad (28)$$

m_{rms} : Stirling engine receiver mass;

$c_{v_{rms}}$: the specific heat of the Stirling engine receiver;

RESULTS AND DISCUSSION

We remind you that we have at the heart of this reflector: a boiler and a Stirling engine.

Figure (3) shows the direct radiation measured on 30_10_21.

This figure shows that the direct radiation for this day varies from 210 W around 8 am to 805 W at 9 am o clock and reaches a peak with a value of 1010 W around 13 pm and decreases to a value of 620 W around 5 pm.

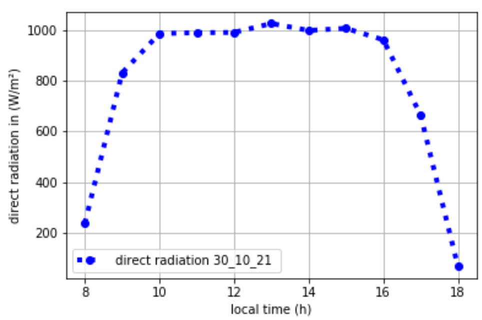

Figure 3 Direct radiation measured on 30_10_21

Figure (4) presents the thermal power receivable at the focus of the parabolic concentrator for a surface of 15 m² which receives the direct radiation presented in figure (3) with the parameters presented hereunder.

We notice that the thermal production for a radiation measured in this day varies from 8010 around 9 am to 10000 W. Remains keeps a value of 10000 W from 10 am to 16 pm. Then goes down slightly to 6000 W towards 5 pm.

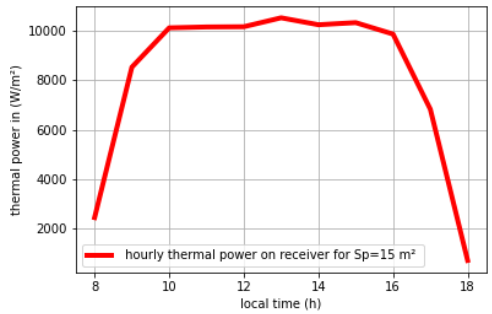

Figure 4 Receivable thermal power at the receiver for a surface of 15 m²

Figure (5) shows the usable thermal power at the two receivers that are at the focus of the parabolic concentrator.

The observation of this figure shows that by eliminating the various losses of thermal transfers presented hereunder, the production varies in turn from 8000 W to 9000 W from 9 am to 4 :10 pm.

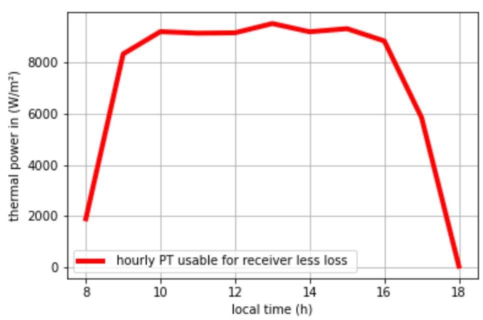

Figure 5 Usable thermal power at both receivers of the parabolic reflector focal point

Figure (6) shows the concentrated temperature at the focus of the concentrator with the direct radiation received during the day of 30_10_21. For a concentration time of 300 s.

The analysis of this figure shows that it is possible to produce a temperature higher than 700°C in 300 s with the direct radiation received from 9 am to 4 pm.

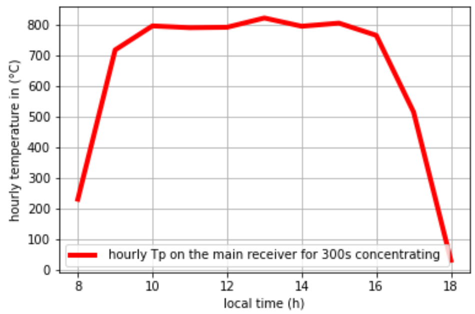

Figure 6 Temperature produced at the focus of the concentrator for an hourly radiation during a concentration of 300s

Figure (7) shows the temperature produced with a direct radiation fixed at 900W. m^{-2} in a concentration time from 0 s to 300 s.

The observation of this figure shows us that in 300 s, we can go from 30°C to 800°C.

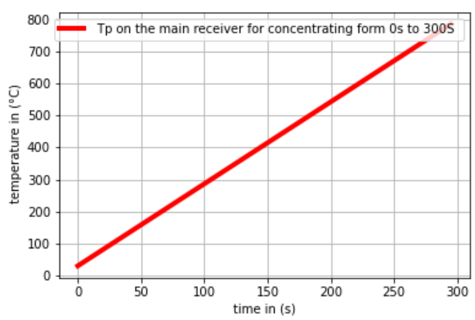

Figure 7 Temperature produced with a fixed radiation of 900W. m^{-2} for a concentration time varying from 0 s to 300 s.

We have just seen in figure (5) that the production of a concentrator with the optimized parameters from 9 am to 4 pm, we can supply in thermal power the two receivers. Among which the boiler and the Stirling engine which need respectively the thermal powers of 4000 W and 5000 W for their operation.

The expression of the heat received by the boiler is deduced from the relation (35):

$$T_c = \frac{Q_{ch}}{m_{ch} \cdot c_{pch}} \times t + T_{amb} \quad (37)$$

With the instantaneous thermal power of 4000 W that the boiler receives, its temperature can be raised from 30°C to about 563°C in 180 seconds (s).

The heat received by the Stirling engine is deduced from the formula (36):

$$T_{msc} = \frac{Q_{rms}}{m_{rms} \cdot c_{vms}} \times t + T_{amb} \quad (38)$$

With an instantaneous thermal power of 5000 W that the Stirling engine receives, we can raise its temperature from 30°C to about 631°C in 120 s.

CONCLUSION

We first performed the thermal analysis and modeled the heat transfers to the two receivers placed at the focal point of a parabolic reflector.

The direct radiation recorded for the day of 30_10_21 reaches a peak with 1010 W at around 1 pm.

The concentrated thermal output at the hearth for the radiation measured in this day varies from 810 around 9 am to 10000 W. This concentrated power keeps a value of 10000 W from 10 am to 4 pm.

It is possible to bring the two receivers respectively the boiler and the Stirling engine from 30°C to a temperature of 563°C in 180 s and from 30°C to 631°C in 120 s with the thermal power concentrated in the focal point.

This study proves and gives the necessary tools to meet the challenge of operating two receivers at the focus of a parabolic concentrator.

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