



Research Article

Performance Evaluation of Spiral Coil Receiver for Thermal Steam Generation Using Optical and Thermal Analysis of Parabolic Dish Concentrator

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ABSTRACT

Solar energy has been advocated as the substitute for depleting fossil fuels for thermal applications and electricity generation. The research was aimed at determining the performance evaluation of the spiral coil receiver for thermal steam generation using a parabolic concentrating system. The parabolic dish solar concentrator (PDSC) with a rim angle of 45° , the focal length of 6.15 m, and an aperture area of 5.8 m^2 were designed and constructed for the determination of the variables. The PDSC and spiral coil receiver were made of stainless-steel reflector sheet and copper tube pipe respectively. Since the PDSC is for high enthalpy steam generation, it can be used for hot water and cooking applications. A finite element stress analysis was carried out to determine the thermal and optical efficiency of the system under various weather conditions. The thermal efficiency and optical analysis of the system were determined and obtained to be 54.4%, and 48.6% respectively. The efficiency according to the finding depends on the optical properties of the materials involved, the geometry of the collector, and the various imperfections arising from the construction of the collector.

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INTRODUCTION

Recently, population growth and industrialization have led to the rise in energy demands across the globe. It is apparent that the conventional resources (Fossil Fuels) are finite and under increasing demand. (Sadik *et al.*, 2013). In addressing the problem of ever-increasing energy demands coupled with saving the depleting fossil fuel resources, solar energy is proved to be a promising source. (Purohit, 2010). Concentrating Solar Power (CSP) systems have effectively reported converting solar energy into heat (Reddy and Veershetty, 2013) with solar dish systems being a more economical source of power and projected to become a key source of renewable energies in the coming years (Poullikkas *et al.*, 2010).

The external receiver could be interesting for low-power applications. In a cavity receiver, on the other hand, a large part of the emitted radiation remains inside the cavity and is absorbed again so that the total radiative heat loss is lower (Ham and Lenz, 1985). The four main types of Concentrating Solar Power (CSP) technology are used to concentrate and collect sunlight in order to turn it into heat. These were namely: parabolic-trough collector (PT), solar tower (ST), linear Fresnel (LF), and parabolic dish (PD). They can be classified according to the focus type (line focus or point one), depending on the receiver type (fixed or mobile), or considering the concentration level (medium or high concentration) (Roldan *et al.*, 2015).

Direct steam generation achieving 90% thermal efficiency at 535 °C with a parabolic dish and cavity type receiver has been reported based on experimental results using a 500 m² dish (Burgess *et al.*, 2011). Pavlović *et al.*, (2016) 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 study would try to find a more efficient and convenient method of harnessing the available solar radiation using concentrating solar collector for solar thermal applications using a spiral coil receiver and encourage the use of friendly technology for domestic and industrial use.

MATERIALS AND METHODS

Materials

The parabolic dish concentrating system was constructed using locally available materials and the specification of the materials used is shown in Table 1. In the selection of materials for the construction, the following were highly considered; local availability, low cost, easy handling during fabrication, lightness of weight for easy handling during use, ability to withstand environmental operating conditions, and non-toxic effects.

A detailed list of the materials, their specifications, and quantities used for the construction of the parabolic dish collector are shown in Table 1.

Experimental Setup and instruments used

The water boiling test experiments for steam generation were performed and the maximum temperature attained for a parabolic concentrating system with a spiral coil receiver was measured by using a Digital thermocouple data logger and recorded, the optical and thermal efficiencies of the systems were also evaluated. The instruments used during instrumentation, include the following listed in Table 2.

Table 1: Specification of Materials Used

MATERIAL	SPECIFICATION	QUANTITY
Stainless steel reflector type	10 m	6
Copper pipe tube	0.4 m	4
Connecting arms	0.35 m	4
Cross bar	0.81 m	1
Adjuster	0.30 m by 0.23 m	1
Receiver sitter	0.51 m	1
Receiver adjuster	0.43 m	1

Table 2: List of Instruments used in the Measurement

PARAMETER MEASURED	INSTRUMENT USED
Solar insolation	Pyranometer
Wind speed	Anemometer
Content temperature	Maximum and minimum mercury in glass thermometer
Ambient temperature	Digital thermocouple data logger
Weight of water and other food substance	Electronic Weighing balance

Methods

Optical Design of the Solar Parabolic Thermal Concentrator

The optical design of the system was done based on the geometry of the dish concentrator. The parabola shape reflector is the meeting point in which distances from a fixed line and a fixed point are equal. Figure 1, shows a parabola, where the fixed line is called the directrix and the fixed-point F , and the focus. The line perpendicular to the directrix and passing through the focus F is called the axis of the parabola. The parabola intersects its axis at a point V called the vertex, which is exactly

midway between the focus and the directrix (Fareed *et al.*, 2012).

A mathematical equation for the parabolic dish solar concentrator in Cartesian and cylindrical coordinate systems was employed (Pavlovic *et al.*, 2016) and is defined as:

$$x^2 + y^2 = 4fz \quad \text{and} \quad z = \frac{r^2}{4f} \quad (1)$$

where x and y are coordinates in the aperture plane and z is the distance from vertex measured along the line parallel with the paraboloid axis of symmetry; f is focal length of paraboloid i.e. distance from the vertex to the focus along the paraboloid axis of symmetry. The relationship between the focal length and the diameter of the parabolic dish is known as

the relative aperture and it defines the shape of the paraboloid and position of a focal point.

Design Description of Solar Parabolic Concentrator

The design of the solar parabolic concentrator was done using a mathematical method.

The parabolic dish solar collector or concentrator comes in twelve parts or pieces like curvilinear trapezoidal petals shaped reflector and is assembled using bolts and nuts to tighten the parts together as shown in figure

2. Each part was made up of light steel material; the upper surface was then fixed or coated with stainless steel reflector sheet in order to have a high efficiency of reflecting the sun energy onto the receiver. Thereafter, the components were assembled into the parabolic dish concentrating system for experimental set up with receiver placed at the focal point for collection of reflected radiation from solar concentrator as shown in figure 3.

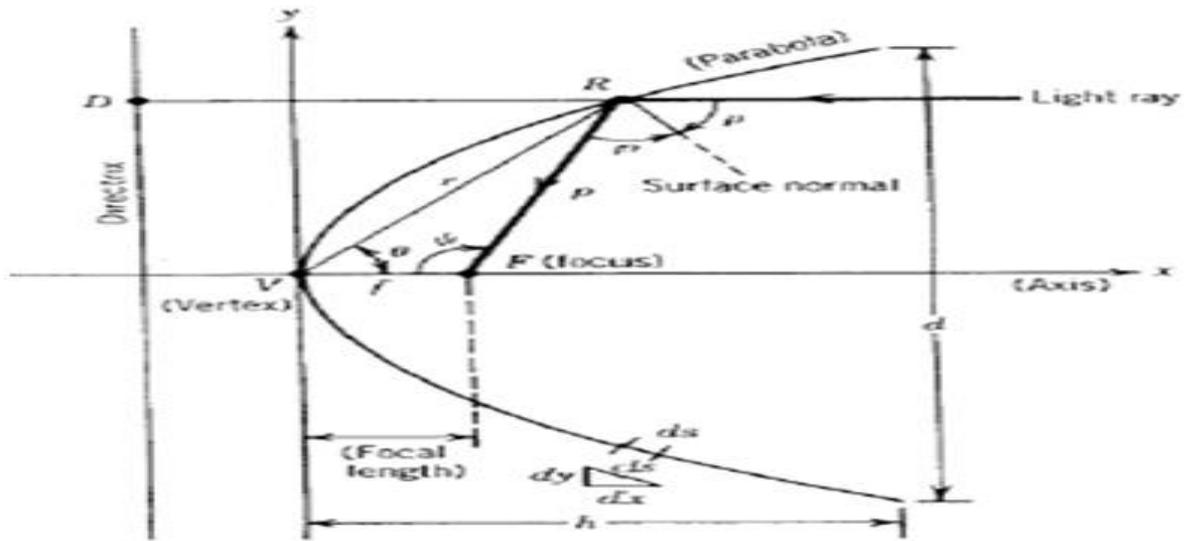


Figure 1: The parabola intersects its axis at a vertex,



Figure 2: Assembled of trapezoidal petal-shaped reflector of parabolic dish concentrator



Figure 3: Parabolic dish concentrating collector

Description of Receiver - absorber

Receiver-absorber placed at the focal point for the collection of reflected radiation from the solar concentrator. In parabolic solar concentrator

design, the minimum size of the receiver should be considered. This is due to the fact that receiver size can reduce heat losses as well as the cost of production. It also increases the

absorbed flux on the surface of the receiver. Copper tube pipe of reasonable diameter was used to construct receiver-absorber, the system of the receiver-absorber for this work was constructed in form of a spiral coil with 24 number of turns and spiral pitch of 13.6 mm. figure 4 and Ffigure 5 show the spiral coil receiver without insulating cover and spiral coil with insulating cover respectively. The insulating cover was made up of glass fiber which was inserted in between two layers

(upper and lower layers) of circular-shaped aluminum plate with a radius greater than that of spiral coil receiver for easier assembling as shown in figure 5. The spiral coil receiver was mounted on the head of the support. Since the parabolic dish collector is a focusing type collector, the receiver was placed at the focus of the parabolic reflector. The geometrical parameters of the spiral coil receiver are described in Table 3.



Figure 4: spiral coil receiver- absorber without insulating cover



Figure 5: Spiral coil receiver- absorber with insulating cover

Table 3: Geometrical parameters of spiral coil receiver

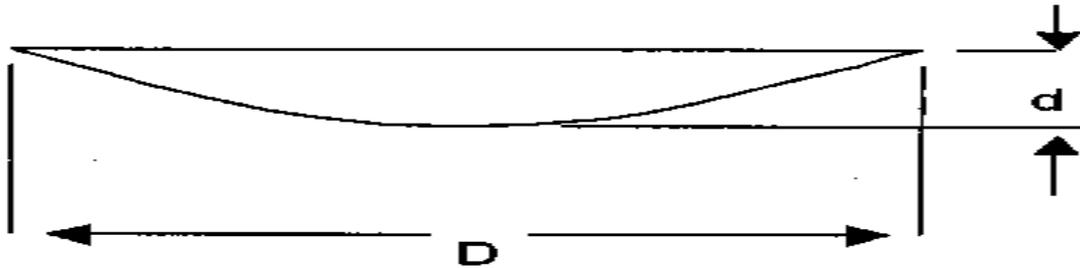
Internal diameter of pipe	9.3mm
External diameter of pipe	12.2mm
Pipe wall thickness	0.25mm
Minimum radius of the coil	25mm
Maximum radius of the coil	202mm
Spiral coil pitch	13.6mm
Number of coils turns	24 turns

Determination of Focal Point of Parabolic Concentrator

In determining the focal point of the dish, two methods are often used: Manual and calculation methods. The latter involves finding the focal point by placing the receiver on the

$$f = \frac{D^2}{4d} \quad (2)$$

where D is the longest width and d is depth of the parabola (NOVA, 2007).

**Figure 6:** Schematic diagram for Determining the Focal Point

Determination of Concentration Ratio of Concentrating Solar Collector

The energy utilization based on the thermal energy parameters and optical efficiency of the system considered and the concentration ratio

$$C_g = \frac{A_a}{A_r} \quad (3)$$

where A_a and A_r are obtained using (4a) and (4b) respectively (Alarcon *et al.*, 2013).

$$A_a = \frac{\pi D a^2}{4} \quad (4a)$$

$$A_r = 2\pi a h \quad (4b)$$

approximate or assumed point till the right point of receiving the highest reflected sunlight is obtained whereas the former was through the use of the equation. In this research, the calculation method was employed as shown in figure 6. Equation 2 was used for the determination of the focal point.

of the collector was determined using equation 3 (Eltahir, 2013). The geometrical concentration ration is defined as the collector aperture area A_a , divided by surface area of the receiver A_r (Eltahir, 2013).

Determination of Thermal Efficiency of Concentrating Solar Collector

Efficiency is defined as the ratio of the thermal power absorbed by the heat transfer fluid to the direct normal irradiance on the aperture area (Najla *et al.*, 2011). The thermal energy efficiency of the parabolic

$$\eta_{th} = \frac{(T_{wf} - T_{wi})M_w C_w}{I_b A_c} \times 100\% \quad (5)$$

where

η_{th} is the Thermal efficiency in %

T_{wf} is the Final temperature of water measured in °C

T_{wi} is the Initial temperature of water measured in °C

M_w is the Mass of water measured in kg

C_w is the Specific heat capacity of water 4200J/Kg/K (Constant)

A_c is the Aperture area of the collector measured in m²

It was 2.45kg of water boiled in 4minutes at solar radiation of 969W/m²and wind speed of 0.47m/s. with the parabolic concentrating system.

The magnitude of the efficiency of the system by 01:00pm was calculated to be $\eta_{th} = 54.4\%$

Evaluation of Optical Efficiency of the Concentrating Collector

The optical efficiency η_o depends on the optical properties of the materials involved (e.g., the reflectance of the dish and the optical properties of the receiver glazing etc.), the geometry of the collector, and the various imperfections arising from the construction of the collector. It can be analyzed by identifying the different loss

concentrating solar collector or reflector depends on the direct normal irradiation I_b , the incidence angle θ_i of the solar radiation, and the operating temperature of the collector (Najla *et al.*, 2011). Therefore, the thermal efficiency was determined using (5) (Najla *et al.*, 2011).

mechanisms (Feuermann and Gordon, 2001).

As the solar parabolic dish concentrator maintains its optical axis always pointing directly towards the sun to reflect the beam, which means the incidence angle of the solar beam into the dish is zero degrees, and the cosine loss equals zero (Palavras and Bakos, 2006). Therefore, the optical efficiency of the collector was evaluated using (6) (Kathori *et al.*, 2012)

$$\eta_{opt} = \frac{Q_{opt}}{I_a A_a} \quad (6)$$

where Q_{opt} the optical energy of receiver and heat transfer is can be calculated using equation (7) (Alarcon *et al.*, 2013).

$$Q_{opt} = A_a \rho_c \tau_v \rho S I_b = 118205.8W \quad (7)$$

Therefore, the optical energy of receiver was found to be 118205.8W

And the optical efficiency η_{opt} was found to be 48.6% using (6)

where I_a is the solar DNI (direct normal irradiance) falling on a collector aperture area, A_a is the aperture area of the collector,

ρ_c is the receptor absorptance, τ_v is transmittance of the reflector, ρ is the reflectivity of the concentrator and S is the shape factor ($S = \frac{A_a - A_t}{A_a}$) and A_t is the fraction of the concentrator aperture area. The values of the optical parameter are described in Table 4.

Table 4: values of optical parameter of parabolic concentrator

Optical parameter	Values
ρ_c Receptor absorptance	0.85
τ_v Transmittance of the glass coating (if it exists).	In this case, it does not exist and then it is equal to 1 (Kathori, <i>et.al</i> , 2012)
A_a Aperture area of collector	5.8m ²
s Shapefactor	0.9996
ρ Reflectivity of the concentrator	0.572

RESULTS

The experimental tests were carried out with a spiral coil receiver at the old site of Sokoto Energy Research Centre at the University's permanent site. Water was selected as the heat transfer fluid for the system because of its stability at high temperatures, low material maintenance, and transport costs, safe to use, and is the most commonly used fluid for domestic heating applications. The tests were conducted for eight weeks, and only three days' results were depicted; from Tuesday 23th to Friday 26th June 2020. On the first and third days, there was evidence of the occurrence of clouds with rapid fall of temperature. This is due to the cloud covering the intensity of solar radiation (uncontrolled factor). Similar results were stated by (Funk, 2000).

Water Boiling Test

The result of the water boiling test is shown in Figure 7. The system shows that the highest temperature recorded is that of the parabolic concentrating system; the corresponding global solar radiation and wind speeds were 948W/m² and 0.70m/s respectively at the time of 13:00 pm on the day of experimentation. The result clearly shows the effect of the atmospheric parameters on the water temperature. It was clearly noticed that the weather was fluctuating due to the cloudy sky which tends to slow down the boiling process. The atmospheric temperature was in constant fluctuation between 75.3 °C to 83.5 °C in between the hours of 11:30 am to 12:30 pm with the highest ambient temperature reached at that same time. The maximum Solar insulation was found between 12:00 pm to 1:00 pm.

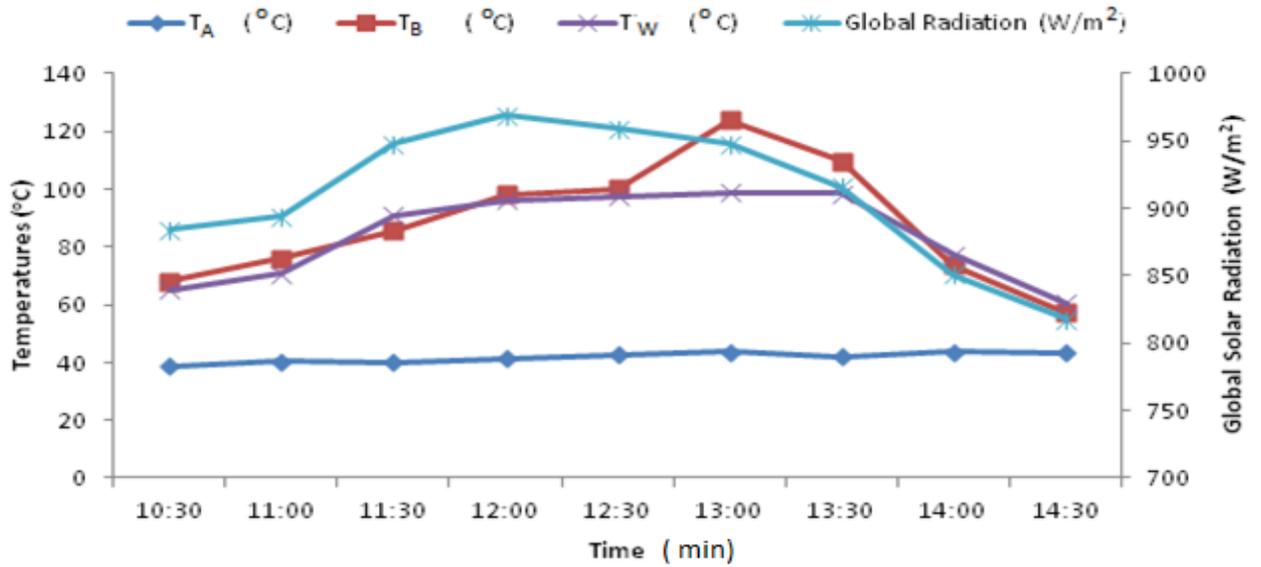


Figure 7: Result of temperature variation with time and corresponding global solar radiation of water boiling test

Steam Test

The steam generation test was conducted on the second day which was having a clear weather. Figure 8, shows the representation of the data in an excel graph. The atmospheric parameters were in favor of the rise in temperature with the highest temperature being attained very fast even

before noon, while the atmospheric temperature was favorable. The highest solar insolation reached and recorded in this clear weather was $884W/m^2$. Comparison between the previous data and this one show that, the later one was being favored by clear sky which makes the boiling point to be reached with little delay.

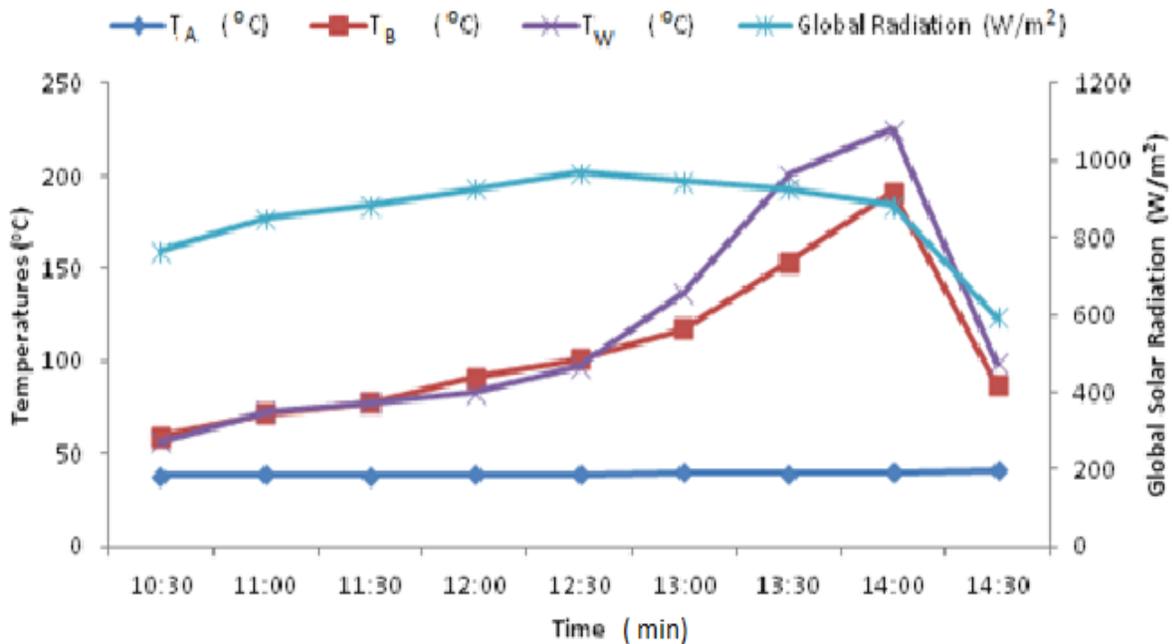


Figure 8: Results of temperature variation with time and corresponding global solar radiation of steam generation test

DISCUSSION

The experimental results obtained from the boiling test was depicted in Figure 7. The Figure shows the results of temperature variation with time and corresponding global solar radiation. The results revealed that the temperature of water obtained by the system was continuously increasing to reach a temperature value of 100°C as the ambient temperature continuously increased to a certain value of 43°C , with a corresponding increase of global solar radiation of $948\text{W}/\text{m}^2$. By 13:00 pm the temperature value of the system was gradually decreased to a certain value, this could be due to a gradual decrease in the intensity of solar radiation and ambient temperature as the result of cloud covered; Therefore, it is uncontrolled parameters or factors, similar results were reported by

Funk (2000) and Serah (2014). Therefore, the maximum temperature required for water to boil was achieved, and a significant limestone was achieved compared to the temperature of 90°C obtained by Aseré *et al.*, (2003). and the temperature value is similar to 100°C obtained by Ibrahim (2012).

Similarly, Figure 8 shows the results of temperature variation with time and corresponding global solar radiation. The results revealed that the highest temperature recorded of the solar concentrating system during steam generation test, corresponding global solar radiation, and wind speed were 225.3°C , $884\text{W}/\text{m}^2$ and $0.40\text{m}/\text{s}$ respectively at time 14:00 pm on the second day of experimentation. On that day the atmospheric condition or weather was

cleared around 12:30 – 14:00 pm. Therefore, the atmospheric parameters were in favor of the rise in temperature with the highest temperature being attained very fast even before noon, while the atmospheric temperature was favourable. The highest solar insolation reached and recorded in this clear weather was 884w/m^2 . Comparison between the previous data and this one show that the latter one was being favoured by the clear sky which makes the boiling point to be reached with little delay, similar results were reported by Funk (2000). The temperature value is lower than 300°C obtained by Kashika and Reddy (2000).

CONCLUSION

The spiral coil receiver with a parabolic concentrating solar collector was found to

be able to produce boiling water and steam with a temperature as high as 100°C and 225.3°C respectively; the system can be used for some domestic and thermal steam applications. The thermal efficiency and optical efficiency were found to be 54.4%, and 48.6% respectively. The variation of temperature results obtained on some days during experimentation could be a result of both optical and thermal losses from the reflector and receiver. Furthermore, the results of the tests conducted were obviously hindered by the fluctuation of the atmospheric parameters as a result of the cloud covering the intensity of solar radiation which is one of the uncontrolled atmospheric parameters, and as well inefficiency caused by manual tracking system or mechanism. But it can be said that a significant milestone was achieved.

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