NIGERIAN AGRICULTURAL JOURNAL
ISSN: 0300-368X
Volume 54 Number 2, December 2023 Pg. 237-246
Available online at: http://www.ajol.info/index.php/naj
https://www.naj.asn.org.ng

An Eco-Friendly Design and Development of Solar Steam Generator

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Abstract

Solar power and wind energy, amongst other renewable energy sources, are abundant in Nigeria's Southern rural regions. Devising ways and means of harnessing and tapping into these natural reserves ensures a regular and steady energy supply and significantly reduces pollution and CO_2 emissions into the atmosphere and environment. This research introduces an environmentally friendly method of capturing solar energy and using the same to boil water to generate steam for agricultural applications in rural areas where electricity is in short supply. The study aims to design, fabricate and evaluate solar steam generator performance. A parabolic dish reflects the sun's rays to a focal point, heating the water in the absorber at this focal position. The ambient temperature of the surroundings was 33^0c when the water heating test was carried out, and the test result shows that at the focal point, the maximum temperature achieved was as high as 187°C. The solar cooker was able to raise the temperature of water to steam within 15 minutes. The results convincingly show that the solar steam generator is a reliable, efficient and alternative method of steam generation for subsistent agricultural applications in southern Nigeria with minimal impact on the Eco-system.

***Keywords*: Renewable energy, Solar power, Steam generator, Eco-system, Environmentally friendly designs**

Introduction

The world's current energy system has been built around the numerous advantages of fossil fuels, and we presently depend overwhelmingly upon them; energy is becoming more expensive and scarce due to the growing population and fast pace of development. Concerns that fossil fuel supplies will 'run out' within the short-to-medium term have likely been overstated, thanks to the continued discovery of new reserves and the application of increasingly advanced exploration technologies. Nevertheless, it remains the case that fossil fuel reserves are eventually limited. Much emphasis and concern have also been placed on the devastating effect of fossil fuel combustion on the environment, and how fuel combustion can be brought down to the minimum has become a case study of research (Denchak, 2016). We all realise today that alternative renewable energy sources will be needed. Renewable energy is derived from natural resources such as sunlight, wind, tides, and geothermal heat. Solar energy in the future is the primary renewable energy source as the sun has vast energy sources. Solar energy from the sun, whether convertible or inter-convertible, forms various forms of energy that make life possible on Earth. Solar energy consists of light and heat the sun emits through electromagnetic radiation. Today's Technology helps capture this radiation and turn it into usable forms of solar energy, such as heat. (Deng *et al.*, 2017).

Solar steam generation is one of the ways solar energy can be utilised appropriately through its conversion to thermal energy. Solar steam generators utilise the simple principles of reflection, concentration, absorption and greenhouse effect to convert sunlight to heat energy (Ashque, 2016). They primarily concentrate the sun's radiation to focus on receivers such as cooking pans, absorbers and pots. The steps involved in the solar cooker are concentrating, capturing and converting the solar energy to heat. The interaction between the light energy and the receiver material helps to convert light into heat by conduction.

Steam generation is currently being done utilising fuels such as LPG, LDO, heater oil or power, which are getting to be costlier and rare the entry of time. Steam solar generation is generally cheaper as sun radiation is abundant in the atmosphere, making the operation cost minimal. Additionally, with solar steam generation, our atmosphere is free from pollutants associated with fuel combustion.

2.1. Material Selection

The selection of materials for constructing this parabolic solar steam generator is essential as the machine's efficiency is highly dependent on the individual performance of the materials. The materials were selected considering the following listed factors (Ikebudu *et al*., 2015).

i.The material properties

ii. Availability of the material

iii.Cost of the material

2.2. Components of the Parabolic Generator

2.2.1 Parabolic Dish

This concave dish is cast iron and lined with an aluminium sheet. Method of a given focus and directrix was employed in constructing the parabolic dish. The plain reflector mirror cut into shapes was glued to the aluminium sheet. In turn, it was riveted to the iron skeleton structure that serves as the reflecting surface of the parabolic dish that converges heat to the base of the copper absorber as in plate 1.

2.2.2 Adjustable Mechanism

The adjustable mechanism of the parabolic dish will be made of metal to support the weight of the parabolic dish and absorber. The primary function is to allow the parabolic dish to align at various angles to capture the sunlight rays depending on the sun's position.

2.2.3 Absorber/ Boiler

The absorber or receiver for this system acts as an absorber, boiler and heat storage unit. The lower external part acts as the absorber, where the reflected light and heat from the parabolic dish are made to focus. It is a copper tube that is spiral in shape. This is the location where the water is heated up to steam. Then, the upper cylindrical part acts as the boiler, where the heated steam is temporarily stored until it escapes through the discharge outlet, as shown in plate 2. Since this system is a demonstrative work, the blade was used to demonstrate the movement of a turbine when acted upon by the steam produced by the system. The blade was positioned strategically directly at the outlet where the discharge of the produced steam takes place. The velocity of discharged steam gives the blade a rotary motion, as in plate 3.

2.2.5 Solar Panel and Pumping System

The water pumping system includes the AC pump, the gate valves and the tube networks. The photovoltaic panel powers the pump. The pump delivers water into the copper absorber through the tube networks. The solar panel and pumping system are shown in plate 4.

2.2.6 Skeletal Structures

These are the framework of the system. It comprises the angle iron, square pipes, circular pipes and metallic rods. They are welded together to form both the base and the adjustment mechanism. They bear the weight of the whole system, as shown in Figure 1.

2.4 Fabrication Process Steps

2.4.1 The Marking out Process

Marking out the required dimensions of the angel iron and the metal pipes together with the square iron bar was the first stage of this fabrication. This will be carried out with precision using the scribers and the try-square.

2.4.2 The Cutting Process

After the required dimensions were marked out, the cutting out of the required breadth and thickness from the primary material was carried out. The cutting out was done on the vice with the hand grinding machine or hacksaw.

2.4.3 The Welding Process

After the first two processes were carried out, the materials were welded together. This involves welding the various frame parts together using the electric arc welding process. The correct welding PPE was worn during this operation to ensure the safety

2.4.4 The Boring Process

After welding, holes were bored into the base to accommodate the bolts and nuts used to fasten the rotating mechanism and other machine parts together. The tedious process was carried out using the drilling machine

2.4.5 The Assembly Process

This comprises the coupling of the machine's various parts, including the parabolic dish, the base, the adjustment mechanisms, the boiler and turbine, and the solar and pumping system.

2.4.6 Gluing **Process**

This process involves cutting plane mirrors into square fragments and then glueing them on the dish's surface with a suitable adhesive. This mirror will now give the dish surface a reflective nature. I used Araldite as the adhesive because of its high bonding strength.

2.4.7 The Finishing Process

This involves all the post-construction activities on the machine, such as filling and painting. Various holes and uneven surfaces on the machine will be filled with a filler material, which is strengthened by a cream hardener, after which the whole set-up is painted with blue Gloss paint.

2.5 Principle of Operation of the System

The parabolic solar stove steam generator lets you capture sunlight to give you astonishing heat, which is then used to generate steam.

It works through the parabolic dish with a reflective (mirror) surface, concentrating direct sunlight on the absorber/boiler at its focal point. Water is deposited into the copper absorber with the help of a solar AC pump through the water hose. The water is then heated to steam at the absorber with the existing valve locked. The steam pressure is then built up in the cylindrical boiler.

When the pressure is high enough, the outlet valve is opened, allowing the steam to escape with a very high pressure. The velocity and pressure of the steam then impinge on the piston of the turbine positioned strategically at the outlet. The piston is then given a translational motion, which is then converted to rotary motion at the turbine disc/blade.

2.6 Design Analysis

2.6.1 Parabolic Dish Geometry

The parabolic dish was selected as a concentrator in this study because it has the potential to meet both the medium and high-temperature needs of humans and has been identified to be the most efficient in terms of heat generation (Prakash *et al.,* 2016). When the sun shines on this concentrator, it reflects its rays to a receiver at its focus point. The parabola occurs when the locus of a point can realign itself such that its distance from a stationary point and a fixed line is always the same (Stine and Geyer, 2017).

This is shown explicitly in Figure 2, where the direction x represents the fixed line, the stationary point is the focus represented by F, and the parabola axis is the imaginary line drawn passing through the point F and at right angles to the direction x. The vertex (V) of the parabola is the point at which the axis of the parabola passes through the parabola, and it is also a point located at the midpoint between the focus (F) and the direction of a parabola as in Figure 2.

2.6.1.1. Focal point

This is the point at which light waves travelling parallel to the axis of the parabola meet after reflecting off its surface. In this set-up, a 1.8m television dish was used; this dish had been made a parabola, and the sizes could not be altered. The dish's diameter (D) and height (h) are 1.8m and 0.3m, respectively. Using equation (1), the focal (f) of the dish is calculated to be 0.675m

$$f = \frac{D^2}{16h} \;\ldots\ldots\; (1)$$

2.7 Rim Angle

The point or extent of truncation of a parabola is often defined in terms of rim angle or the ratio of focal length to aperture diameter (f/d). It has been a problem that the smaller the rim angle, the further the focal point moves away from the parabolic curves. Also, the parabolas with the higher rim angles are less flat and more profound and have their focal point closer to their parabolic curves (Craig, 2015). The rim angle, ψrim, can be found in the dish dimensions (Mohammed, 2013). Using equation 2, the rim angle ψ_{rim} is gotten to be 67.38^0

$$\tan \Psi_{rim} = \frac{1}{\frac{D}{8h} - \frac{2h}{d}} \;\ldots\ldots\; (2)$$

The parabolic dish aperture area is most important to the solar energy designer. It is simply the circular area defined by diameter D. The aperture area (A_0) is computed to be 2.54m^2 using equation 3.

$$A_0 = \frac{\pi D^2}{4} \;\ldots\ldots\; (3)$$

The aperture is explicitly obtained using equation 4.

$$A_0 = 4\pi f^{\,2} \frac{\sin^2 \Psi_{rim}}{1 + \cos \Psi_{rim}} \;\ldots\ldots\ldots\; (4)$$

2.8 Absorber Design

The absorber is the boiler's lower external part at the dish's focal point. For improved efficiency of an indirect solar cooker using a parabolic reflector, cavity receivers were encouraged (Al-sound *et al.*, 2010);(Zawilksa and Brooks, 2011). Therefore, an innovative cavity receiver was designed to maximise the heat flux from this system's dish. Several cavity receivers were considered by(Kueh and Goldsteen, 2006). This was the first effective solar cavity receiver in a horizontal circular design. For better conduction, the absorber is made of copper tube with the following dimensions: Outer d_0 is 7.0mm, inner diameter d_i = 6.5mm and the length of the length (L) is 2560mm. Consequently the actual volume of the absorber (V) which is given by V_0 - V_I is 1.35 x 10^{-5}m^3 using equations 5 and 6 to obtain equation 7.

$$\text{Outer volume } V_0 = \pi L \frac{D^2}{4} \;\ldots\ldots\; (5)$$

$$\text{Inner volume } V_I = \pi L \frac{D^2}{4} \;\ldots\ldots\ldots\; (6)$$

$$V = V_0 - V_i \;\ldots\ldots\ldots\; (7)$$

The surface area of the absorber (A_{abs}) is computed using equation 8 as 0.196m^{2,} where the surface diameter of the formed spiral shape of the copper absorber (d) is 0.5m. The mass of the absorber is obtained using equation 9.

$$A_{abs} = \pi \text{ x } \frac{2}{4} \;\ldots\ldots\ldots\; (8)$$

Mass of absorber = density x volume ……… (9)

The mass of the absorber is 0.12kg, where the density of copper is 8960kg/m^3.

2.9 Geometric Concentration Area

The concentration ratio is defined as the geometric ratio of the aperture area of the collector to the entrance surface area of the receiver cavity, as shown in Equation 10. It is the basis used to measure the intensity of the reflected rays. (Aldossary *et al.*, 2019)

Geometric concentration C_{area} is defined as the ratio of aperture area to absorber area and is computed using equation 3.10 as 12.96

$$C_{area} = \frac{A_0}{A_{abs}} \;\ldots\ldots\ldots\; (10)$$

2.10 Expected Thermal Performance of the System

2.10.1 Thermal Efficiency

The volume of the boiler cylinder (V_b) from equation 11 is 2998m^3

$$V_b = \frac{\pi {d_b}^2}{4} \;\ldots\ldots\ldots\; (11)$$

10% of the boiler volume is used for better thermal conductivity of the system. Hence, the total volume of water in the system V_w is obtained using equation 12 (3.85x10^{-4}m^3)). Consequently, the total volume of water in the system M_w is 3.81kg, given that the density of water is 997kg/m^3.

Volume of water (V_W) = inner volume of the absorber volume of boiler cylinder +1/10 volume of boiler cylinder

$$V_w = V_0 + \frac{V_b}{10} \text{ …….. (12)}$$

Assuming that the initial temperature of the absorber and the water are both at 25°C (room temperature) and the final temperature of both is 100°C (steam temperature). The heat needed to achieve this temperature increment is 1203kJ, computed using equation 13. Where the specific heat capacity of water C_w and the specific heat capacity of copper absorber C_{abs} are 4200j/kgK and 385j/kg respectively.

$$Q = [MC\Delta\theta]_{abs} + [MC\Delta\theta]_w \text{ ………(13)}$$

2.10.2 Solar Insolation

This is the amount of electromagnetic energy (solar radiation) incident on the surface of the Earth. By knowing this, we can determine the amount of energy the boiler will produce. The average insolation (I_b) recorded for the city of Owerri in September is 35.13MJ/m^2/day, or 406.45W/m^2 In W/m^2.

2.10.3 Time Taken To Produce Steam

The time taken to raise 3.81kg of water from 25°C to steam is 38.86 minutes, as given by equation 14. The thermal efficiency range of most solar concentrations is 40% - 60 %(Mohammed, 2013)

th=0.5 (average of 0.4 and 0.6)

$$Q = \eta_h I_b At \text{ …….. (14)}$$

2.10.4 Power of the Dish

Power of heating is the ratio of the energy used in producing a given mass of steam to the time taken using equation 15;

The power required to raise 3.81kg of water to the team is 525.96W;

$$P = \frac{\text{energy used}}{\text{time taken}} \text{ ……… (15)}$$

2.10.5 Heat Flux

Heat or thermal flux is the amount transferred per unit per unit of time from/to a surface. It is computed as 514kj/m^2 using equation 16

$$q = \frac{Q}{A_0} \quad \text{ ……… (16)}$$

2.10.6 Heat Transfer Rates

The transfer of heat within the parabola uses three means of heat transfer:

I. Conduction

ii. Convection

iii. Radiation

2.10.7 Heat transfer by conduction

This occurs between the absorber and the fluid (water) being heated in formulating the expression for heat transfer by conduction. The walls of the absorber are treated as a plane wall. The Coefficient of Thermal Conductivity of copper (K) is 386$Wm^{-1}k^{-1}$ (Carvil, 2017) and the cross-sectional area of the absorber is given. Hence, using equation 17, the quantity of heat transfer by conduction is 6137kj/m^2

$$Q_0 = -kA\left[\frac{d\theta}{dt}\right] \text{ ……… (17)}$$

2.10.8 Heat transfer through convection

This is the heat transfer between the layers of the fluid. When the heat is conducted into the absorber, the fluid immediately adjacent to it forms a thin region called a boundary layer that sweeps it away(Rajsput, 2009). Mathematically, the rate of heat transfer by convection in the system is computed as given in equation 18;

$$Q_1 = H_c A(\Delta\theta) \text{ …….. (18)}$$

$$Q_1 = 13.75 x 0.196 x (100 - 25) = 202.12 J/m^2$$

Where;

H_C= Convection heat transfer coefficient (*W/m*^{2}°C). 2.5-25w/mk an average of13.75w/mk for free air (Kosky and George, 2013)

A = Cross-sectional area of the absorber m^2

Q_1= rate of heat transfer (j/m^2)

$\Delta\theta$ = Temperature difference °C

2.10.9 Heat transfer by radiation

Transmission by radiation is the primary means of heating the absorber. Thermodynamic principles and consideration show that an ideal thermal radiator will emit energy at the rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area. Thus, equation 19 was used to obtain the rate of heat transfer by radiation;

$$Q_2 = \sigma A_0 T^4 \text{…….. (19)}$$

Where,

Q_2= rate of heat transfer by radiation (w)

σ = Stefan-Boltzmann constant 5.669x 10^{-8}W/m2k^4

A = area of the emitting surface (m^2)

T = temperature of the absorber in thermal equilibrium with the fluid 100°C or 373K

2.11 Stress Analysis

2.11.1 Thermal stress

Since the system is subjected to the sun's high temperature, thermal stress is induced in the components. These stresses tend to bring about an expansion in the system. Since the ends of the dish are fixed (Welded) to rigid support so that its expansion is prevented, the thermal stress induced on the dish plate is determined using equation 20;

$$\sigma = \mathcal{E} \in = \alpha.t.\in \text{…….. (20)}$$

Linear expansivity of mild steel a =12x10^{-6}

Modulus of elasticity ∈ = 200 x 10^6N/m^2

Assuming that thermal stresses set in at the temperature of 373k

$\sigma = 12x10^{-6} x 373 x 200x10^6 = 895.2 x 10^3$ *N/m*^{2}

Results and Discussion

Temperature Variation

Upon completing the fabrication of the parabolic solar stove steam generator, a temperature variation test was performed to evaluate the relationship between the ambient temperature and the generated focal point temperature. The testing was conducted in September for four bright days. The whole assembly was kept in an open space from 9:0am to 5:00 pm. A pyrometer was placed at the focal point to obtain the focal point temperature. The temperature of the atmosphere was also measured. The recording was done every 10 minutes, and the maximum temperature recorded in the hour range is tabulated in Tables 1 to 4. The average ambient temperature and focal point temperature of the time of test for the four days are then computed and shown in Table 5. The graph of mean ambient temperature and mean focal length temperature was plotted against time, as shown in Figure 3. The graphs show that low-temperature values were recorded in both ambient and focal point temperatures in the early and late hours. Also, the two graphs follow the same trend. That implies a relationship between the ambient temperature and focal point temperature. The higher the ambient temperature, the higher the focal point temperature. More so, it can be seen that the maximum temperature of 224.5°C was generated from the focal point at 12 – 1 pm, followed by a temperature of 224.25°C at 1-2 pm. This shows that the best time to make use of this parabolic generator is from 12 -2 pm of the day because the sun is directly overhead at this time of the day.

Water Heating Test

This test aims to determine the parabolic steam generator's heating rate. In this test, the temperature of the water/steam is measured at intervals of 1½ minutes for 15 minutes using a pyrometer. The values are tabulated as shown in Table 6. From Figure 4, the water was initially at room temperature, which is 25°C. The concentrated heat at the focal point gradually raises the temperature of the water. It took approximately 6 minutes for the water to attain its boiling point (100°C), after which the steam generation commenced, and the fluid's temperature continued to rise until it attained a maximum temperature of 184°C. It took the system 15 minutes to raise the temperature at the focal point from 25°C to 184°C.

Cost Analysis of the Machine

The materials fabricating various components of the Balling disc Machine and labour costs were quantified and presented in the Bill of Engineering Materials, as shown in Table 7. Therefore, the total cost of producing one unit of the balling disc machine is one hundred and sixteen thousand, three hundred and sixty naira (N166, 360).

Conclusion

In conclusion, the need for constructing a parabolic dish solar steam generator arose as an alternative to solve the thermal energy needs of the populace. This will also reduce the total dependency on fossil fuels and other non-renewable and exhaustible energy sources known to be depleted with ages to come as they are being used up. As such, deforestation and other environmental populations are reduced to a minimum. The need to utilise the free natural resource in abundance requires no recurrent expenses as another energy source. Thus, it is regarded as the cheapest source of fuel for a man. The project cost was minimised by sorting for locally available materials, and the highest temperature at the focal point during the day was above 200°C. The following recommendations are therefore made for the design, construction and use of a parabolic steam generator. A silver or gold mirror reflector should be used instead of a plane mirror, as those two have a much better reflective result than the plane mirror. Since the intensity of the sun is higher in the northern part of Nigeria. I recommend the use of this generator in the north. Instruments such as a pyrometer and calorimeter should be provided, which would aid in better analysis of the results of solar cookers.

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Plate 1. Parabolic dish

Plate 2: The Absorber

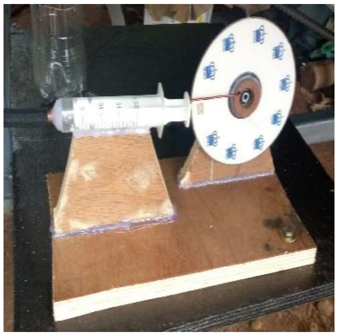
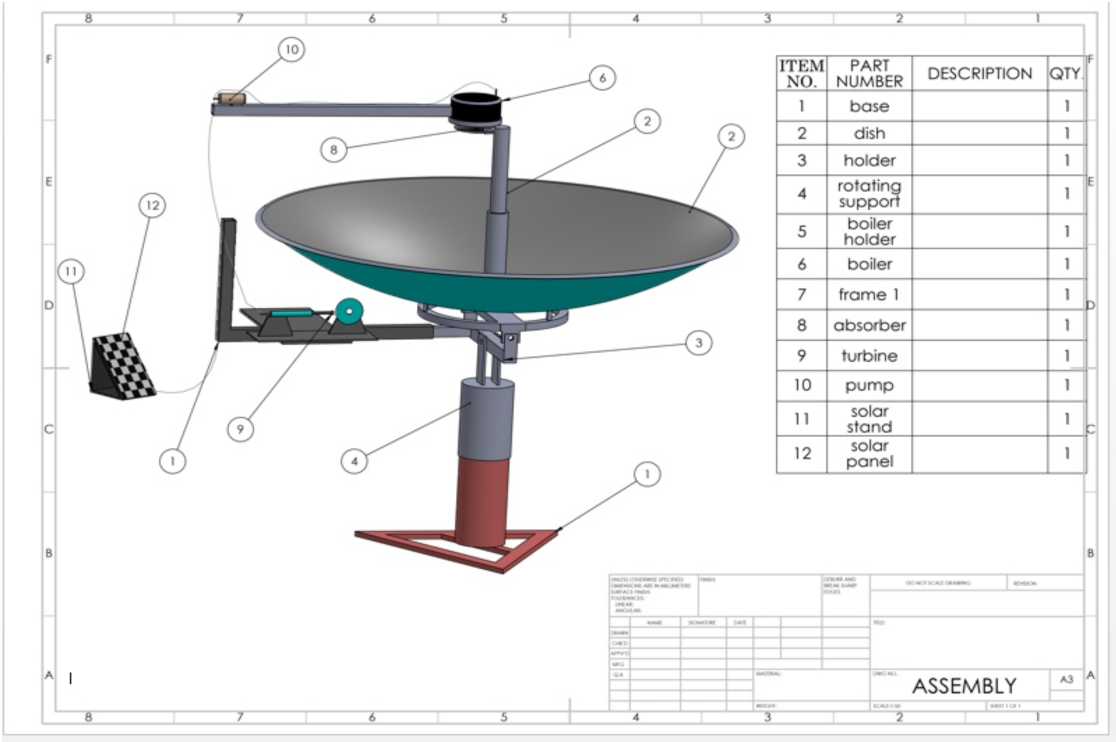


Plate 3: Demonstration turbine

Plate 4: Solar panel and pumping systems



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	base		1
2	dish		1
3	holder		1
4	rotating support		1
5	boiler holder		1
6	boiler		1
7	frame 1		1
8	absorber		1
9	turbine		1
10	pump		1
11	solar stand		1
12	solar panel		1

Figure 1: Parts Listing Of the Steam Generator

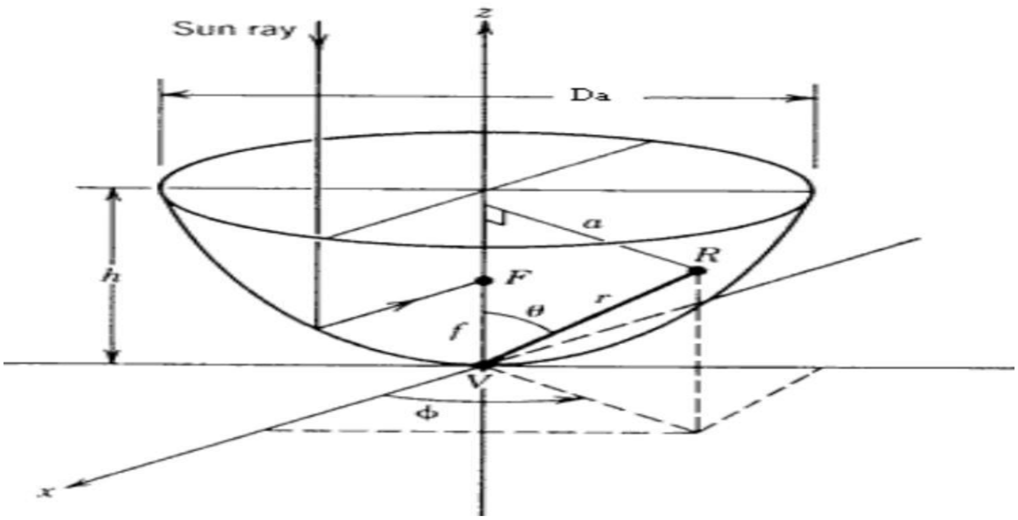


Figure 2: Geometry of a parabola (Stine and Geyer, 2017)

Table 1: Temperature variation recorded for day 1

Time	Ambient Temp.(°C)	Focal Point Temp. (°C)
9 – 10 am	28	104
10 – 11a	30	153
11 – 12 pm	30	187
12 – 1 pm	31	223
1 – 2 pm	31	213
2 – 3 pm	31	195
3 – 4 pm	32	198
4 – 5 pm	31	165

Table 2: Temperature variation recorded in day 2

Time	Ambient Temp. (°C)	Focal Point Temp. (°C)
9 – 10 am	29	109
10 – 11a	30	145
11 – 12 pm	31	175
12 – 1 pm	34	210
1 – 2 pm	33	235
2 – 3 pm	33	215
3 – 4 pm	32	185
4 – 5 pm	32	139

Table 3: Temperature variation recorded on day 3

Time	Ambient Temp (°C)	Focal Point Temp (°C)
9 – 10 am	29	111
10 – 11a	30	127
11 – 12 pm	31	194
12 – 1 pm	33	235
1 – 2 pm	32	226
2 – 3 pm	31	212
3 – 4 pm	30	197
4 – 5 pm	28	117

Table 4: Temperature variation recorded on day 4

Time	Ambient Temp (°C)	Focal Point Temp (°C)
9 – 10 am	30	107
10 – 11a	31	136
11 – 12 pm	33	184
12 – 1 pm	35	229
1 – 2 pm	34	224
2 – 3 pm	32	213
3 – 4 pm	31	191
4 – 5 pm	30	152

Table 5: Mean temperature variation of the four days

Time	Mean Ambient Temp. (°C)	Mean Focal Point Temp(°C)
9 – 10 am	29.00	107.00
10 – 11a	30.25	140.00
11 – 12 pm	31.25	185.00
12 – 1 pm	33.25	224.50
1 – 2 pm	32.50	224.25
2 – 3 pm	31.75	208.75
3 – 4 pm	31.25	192.75
4 – 5 pm	30.50	143.25

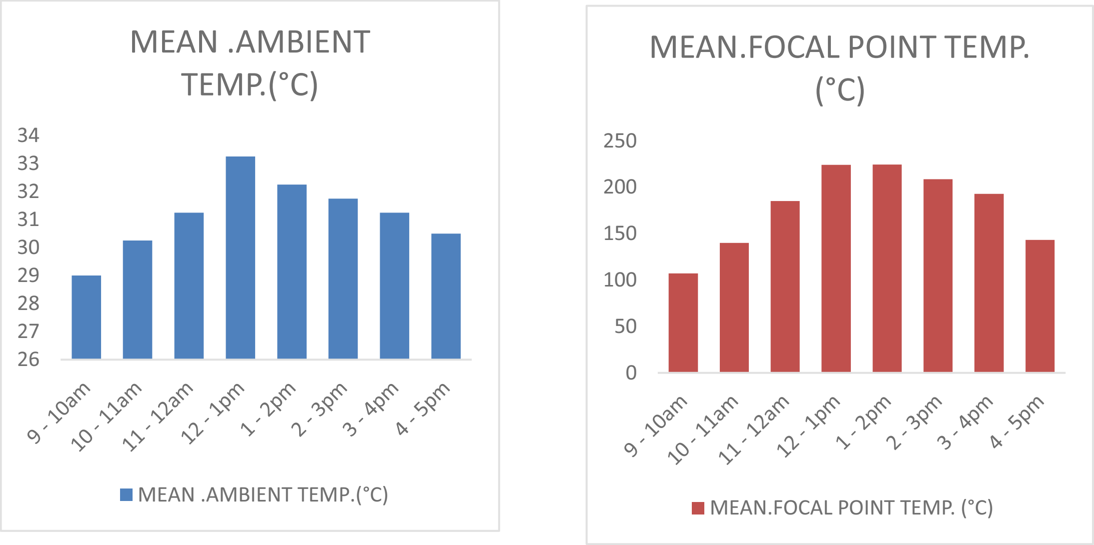
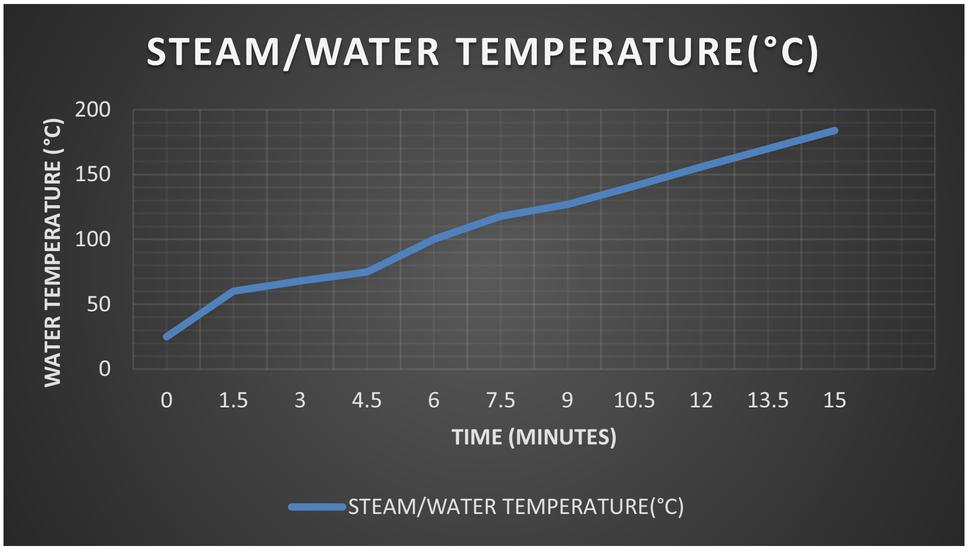


Fig 3. Graphical representation of the mean ambient and mean focal point temperature

Table 6: Rate of Water heating test

Steam/Water Temperature(°C)	25	60	68	75	100	118	127	141	186	170	184
Time (Mins)	0	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15



` ***Fig. 4: Graph of steam/water temperature against time***

Table 7: Bill of materials

S/N	Materials	Unit Cost (N)	Quantity	Amount (₦)
1	Parabolic dish	20,000	1	20,000
2	Mirror	4,000	3	12,000
3	Water Pump	3,000	1	3,000
4	Pump switch	100	1	100
5	Solar Panel	18,000	1	18,000
6	Steam gate valve	5,000	1	5,000
7	Watergate valve	1,000	1	1,000
8	Boiler/Absorber	40,000	1	40,000
9	Fibreglass	10,000	1	10,000
10	Adhesive gum	2,000	3	6,000
11	Water hose	400	3yrds	1,200
12	Paint	5,000	1	5,000
13	Bolts	10	6	60
14	Labour	50,000		50,000
			Total.	166,360