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Research Article

ANALYSIS OF THERMAL AND OPTICAL EFFICIENCY OF PARABOLIC CONCENTRATING SYSTEM FOR THERMAL APPLICATION

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Abstract

Solar power generation is the most promising technology to transfer energy consumption reliance from fossil fuel to renewable sources. Concentrated solar power generation is a method to concentrate the sunlight from a bigger area to a smaller area. The collected sunlight is converted more efficiently through two types of technologies: concentrated solar photovoltaic's (CSPV) and concentrated solar thermal power (CSTP) generation. In this research work, these two technologies would be evaluated in terms of system construction, performance characteristics, design considerations, cost benefit analysis and their field experience. The two concentrated solar power generation systems would be implemented with similar solar concentrators and solar tracking systems but with different energy collecting and conversion components: the CSPV system will use high efficiency multi-junction solar cell modules, while the CSTP system will use a boiler -turbine-generator setup. The performances would be calibrated via the experiments and evaluation analysis.

Keywords: Solar energy, solar thermal collectors, Linear parabolic collectors, compound parabolic collectors, solar thermal systems.

INTRODUCTION

Energy consumption has increasing rate worldwide because of the new trends in lifestyle. With threats of global warming and increased energy cost, the use of renewable and sustainable energy sources is becoming more and more popular. Solar energy is the most abundant and its usage is the more widespread. Solar collectors are heat exchanger devices that capture the incident solar irradiation and transform a part of this to useful heat. This heat is given to a working fluid in order to be transferred to the load or to the storage device. The temperature level of the working fluid determines its energy flow which is also a crucial parameter for high temperature applications. In order to increase the temperature of the working fluid and its energy rate, concentrating collectors are used in many applications. The solar thermal collectors have been widely used to concentrate solar radiation and convert it into useful heat for various thermal processes. Characteristics of solar thermal collectors, especially the concentrating type, are well established in research literature and have many applications in industry and for domestic water heating, and steam generation (CSTE, 2004)The operation principle of solar concentrating collectors is the focusing the incident solar radiation onto a small area known as receiver. Many types of concentrating collectors are available, with various concentrating ratios and different operating temperature levels. Linear parabolic collectors, compound parabolic collectors, Fresnel collectors, and solar dish collectors are the most widespread concentrated collectors. Generally, solar thermal utilization can be separated to low, medium, and high temperature systems. The low temperature solar systems, which operate without sunlight concentration, have low conversion efficiency and they are used in domestic applications. The medium and high temperature solar thermal systems, which require sunlight concentration, have higher conversion efficiency and they can used in great variety of applications (Pavlović,2016)

Statement of the problem

There are still millions of people living in electricity-poverty without enough electricity to support their basic needs, such as food, medicine, home heating, cooling etc. in Nigeria particularly northern part of the country e.g Sokoto state. Many places where these people live have great potential of solar energy resource. Distributed solar power generation could be a quick alternative way to help these poor people to obtain electricity in an economic and environmental friendly way without the high cost centralized power plants and power distribution system (Sadik *et al.,* 2013). With the advancement of the modern technologies, there are more effective solutions to utilize solar energy to improve our quality of life and be beneficial to the environment as well.

Significance of the study

Solar power is compatible for both urban and rural remote areas, as well as good for both residential and utility scale development. Solar energy will become the main energy resource of our planet with advancement in solar technology research to lower cost and improve energy conversion efficiency. Access to affordable energy is one of the basic requirements for development and for poverty reduction. Many areas have about 80% of the population living out of reach of the electrical grid, and where the main energy source is fire wood as reported by (Sadik *et.al,* 2013). Deforestation is already a severe problem, and increasingly so as the population increases. Therefore, concentrating solar collector for thermal steam generation system can fill the gap or compliment non renewable energy sector for the purpose, of transformation and remediation on the stated problems.

Aim and objectives

The aim of this research is to develop a parabolic concentrating solar collector for steam thermal application.

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The objectives are:

- Investigate the optical performance of a parabolic concentrating solar collector.
- Design an optimal receiver for the air based heat transfer system
- Investigate the thermal performance of the collector.

LITERATURE REVIEW

The solar thermal collectors have been widely used to concentrate solar radiation and convert it into useful heat for various thermal processes. Characteristics of solar thermal collectors, especially the concentrating type, are well established in research literature and have many applications in industry and for domestic water heating, and steam generation Ali (2013). The operation principle of solar concentrating collectors is the focusing the incident solar radiation onto a small area known as receiver. Many types of concentrating collectors are available, with various concentrating ratios and different operating temperature levels. Linear parabolic collectors, compound parabolic collectors, Fresnel collectors, and solar dish collectors are the most widespread concentrated collectors. Generally, solar thermal utilization can be separated to low, medium, and high temperature systems. The low temperature solar systems, which operate without sunlight concentration, have low conversion efficiency and they are used in domestic applications. The medium and high temperature solar thermal systems, which require sunlight concentration, have higher conversion efficiency Reddy *et al.,*(2013) and they can used in great variety of applications.
Ali (2013) has presented a study that aims to develop a 3-D static solar concentrator that can be used as low cost and low energy substitute. Their goal was to design solar concentrators for production of portable hot water in rural India. Qianjun *et al.,* (2013) has investigated on the photo-thermal conversion efficiency in order to improve the cost effectiveness of the examined solar system. They used the Monte Carlo ray tracing method for calculating the radiation flux distribution on the receiver and the ANSYS Fluent for calculation of radiation and convection heat transfer mechanisms. Their results proved that the maximum energy efficiency was about 52% when the direct normal irradiation was 800 W/m^2.

Eswaramoorthy and Shanmugam (2012) investigated the thermal efficiency of solar a cooker with parabola diameter of 3.56 m and total aperture of 10.53 m^2, with a finally thermal efficiency of 60%. Reddy *et al.,* (2013) have experimentally investigated a solar parabolic dish collector with 20m^2 aperture in order to investigate its performance with the examined modified cavity receiver. The average value of the overall heat loss coefficient was found to be about 356 W/m^2. Jones and Wang (1995) computed the flux distribution on a cylindrical receiver of parabolic dish concentrator using geometric optics method. Parameters such as concentrator surface errors, pointing offset errors and finite sun shape were taken into consideration in the geometric optics methods. Takkar *et al.,* (2015) have investigated the possible use of parabolic dish collector in process industries. They presented a mathematical model for heating application using thermal oil. Blazquez *et al.,* (2015) described optical test for the DS1 (parabolic Stirling dish) prototype, a study that was carried out by CTAER. The aim of this investigation was to characterize the optical parameters of DS1 prototype. The results comparison proved that the dish surface had an average optical error of 2.5m rad and an estimated spillage value of 7%, for the examined geometry. Li *et al.,* (2013) presented the radiation flux distributions of the concentrator-receiver system by Monte Carlo ray tracing. The final radiation flux profiles were subsequently transferred to a CFD code as boundary conditions in order to simulate the fluid flow and the conjugated heat transfer in the receiver cavity by coupling the radiation, natural convection, and heat conduction numerically. Pavlović *et al.,* (2016) presented an optical design and ray tracing analysis of a solar dish concentrator composed of 12 curvilinear trapezoidal reflective facets made from solar mirror with silvered coating layer. A more recent study reported that 95% of the insulation reflected from a 500 m^2 dish (mirror reflectivity of 93.5%) was focused into a cavity type receiver with an aperture of 500 mm diameter (Lovegrove *et al.,* 2011).

Principle of Physics Adopted

The basic principle adopted in the construction of the parabolic concentrating solar steam collector is that when parallel rays of light from the sun close to and parallel to the principal axis are incident on a concave or parabolic shaped mirror, they converge or come together after reflection to a point F on the principal axis called the principal focus as shown in Figure 1

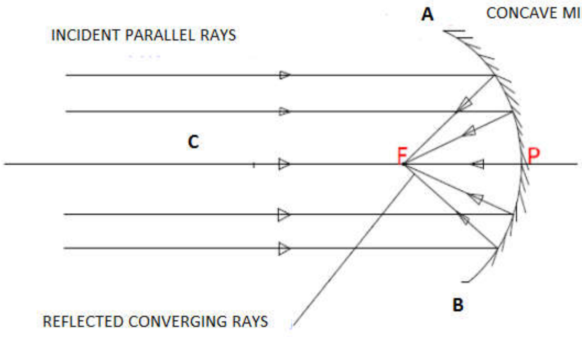

Figure 1. Parabolic dish (source Folaranmi, 2009)

Where
F is the principal focus
P is the pole
C is the centre of curvature
AB is the aperture is the width of the mirror.

The thermal radiation from a high temperature body to a lower temperature body causes transfer of heat through electromagnetic waves up to 0.1μm to 3μm. Thermal radiation is in the infrared range and travels at the speed of light. When radiation strikes a body, a part is reflected, another is absorbed, and the remainder is transmitted through if the body is transparent. The law of conservation of energy dictates that the total sum of radiation components must be equal to incident radiation, i.e.

RESEARCH METHODOLOGY

Design Consideration

A dish Stirling system or concentrating solar collector system would comprises of a parabolic dish concentrator, a thermal receiver, and a Stirling engine position would be at the focus of the dish; the whole system would be mounted on a structure that tracks the sun by pivoting on one or two axes (Abbas, 2008).

Fig. 2; shows a parabola which has a locus of a point that moves so that its distances from a fixed line and a fixed point are equal, where the fixed line is called the directrix and the fixed point F, the focus. The length FR equals the length RD. 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, 2012).

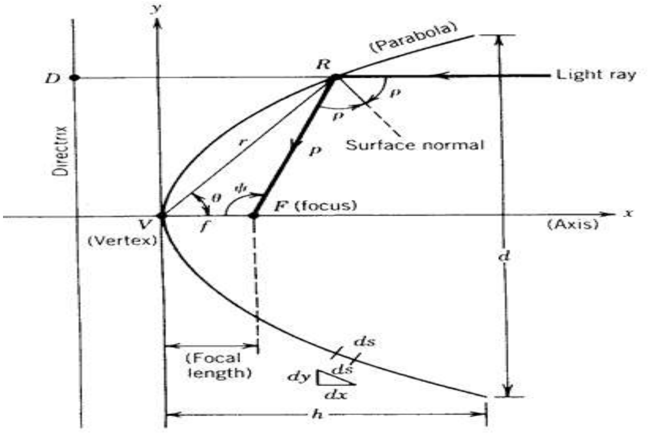

Fig 2. The Parabola

If the origin is taken at the vertex V and the x-axis along the axis of the parabola, the equation of the parabola is given by:

$$y^2 = 4fx \qquad (1)$$

where x = h i.e. the dept while f is the focal length between the vertex and focus, when the origin is shifted to the focus F as is often done in optical studies, with the vertex to the left of the origin, the equation becomes;

$$y^2 = 4f(x-f) \qquad (2)$$

In polar coordinates, using the usual definition of r as the distance from the origin and θ the angle from the x-axis to r, we have for a parabola with its vertex at the origin and symmetrical about the x-axis;

$$\frac{\sin^2\theta}{\cos\theta} = \frac{4f}{r} \qquad (3)$$

Usually, in solar studies, it is more useful to define the parabolic curve with the origin at F and in terms of the angle (ψ) in polar coordinates with the origin at F. The angle ψ is measured from the line VF and the parabolic radius p, is the distance from the focus F to the curve. Shifting the origin to the focus F, Vanita *et al, (*2015) describe it as:

$$p = \frac{2f}{1+\cos\omega} \qquad (4)$$

The parabolic shape is widely used as the reflecting surface for concentrating solar collectors because it has the property that, for any line parallel to the axis of the parabola, the angle p between it and the surface normal is equal to the angle between the normal and a line to the focal point. Since solar radiation arrives at the earth in essentially parallel rays and by Snell's law the angle of reflection equals the angle of incidence, all radiation parallel to the axis of the parabola will be reflected to a single point F, which is the focus and then the following is true:

$$\psi = 2p \qquad (5)$$

ψ is the angle of reflection and P is distance RF. The general expressions given so far for the parabola define a curve infinite in extent. Solar concentrators use a truncated portion of this curve. The extent of this truncation is usually defined in terms of the rim angle (ψ_{rim}) or f/d which represents the ratio of the focal length (f) to diameter of dish (d). The scale (size) of the curve is then specified in terms of a linear dimension such as the aperture diameter d or the focal length f. This is readily apparent in Fig 3 below which shows various finite parabola having a common focus and the same aperture diameter:

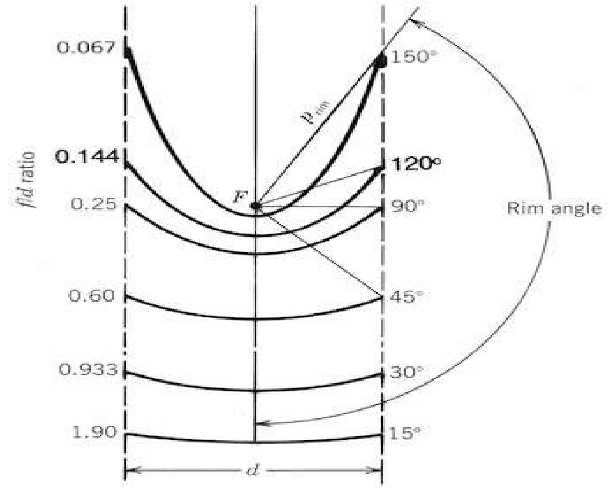

Fig. 3. Segments of a parabola having a common focus F and the same aperture diameter

$$h = \frac{d^2}{16f} \qquad (6)$$

In a like manner, the rim angle (ψ_{rim}) may be found in terms of the parabola dimensions:

$$\tan\psi_{rim} = \frac{1}{(d/8h) - 2h/d} \qquad (7)$$

Another property of the parabola that may be of use in understanding solar concentrator design is the arc lengths. This may be found for a particular parabola. From Equation (7) by integrating a differential segment of this curve and applying the limits x = h and y = d/2.

Locating the focal point of the dish

In locating the focal point of the dish, two methods are often used: Manual construction which entails finding the focal point by placing the receiver on the approximate or assumption point till the right point of receiving the highest reflected sunlight is gotten or through the calculations (equation) method. In this work, the calculation (equation) method which entails using the parabola equation to calculate the required parameter was adopted. Referring to fig 4, the focal point would be calculated using equation (8) below:

$$f = \frac{D^2}{4d} \tag{8}$$

where D is the longest width (NOVA, 2007). The steps are as follows

Step 1: The longest diameter (width) of the parabola up to its rim was measured to be 252m

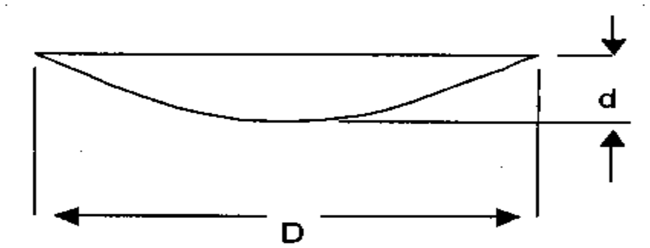

Fig. 4. Schematic diagram for determining the focal point

Step 2: Divide the diameter by two i.e. $\frac{1}{2} \times 252$ to determine the radius y,we have y = 126m Step 3: Square the radius i.e. $y^2 = (126)^2 = 15{,}876$

Step 3: Measure the depth of the parabola (d) from its vertex .i.e. (42m) and multiply it by 4. i.e. $4d = (4 \times 42) = 168m$
Step 4: substituting into equation 23 gives the focal point i.e. $\frac{15{,}876}{168} = 94.5m$

Construction Procedure

The main components of a Parabolic Dish Solar Concentrator (PDSC) are: The Parabolic dish, the Support and the Receiver,

Solar Dish Concentrator Design: The parabolic dish concentrator has six segmental parts for easier transportation to be assembled using bolts and nuts to tight them together. Each part would be made up of light steel material; the upper surface would be coated with an aluminium foil reflector sheet or thin foil reflective aluminum sheet in order to have a high efficiency of reflecting sun energy onto the receiver. After finishing the coating, the segmented part of the parabolic dish would be connected together to be fixed into the parabolic dish shape. The whole system would be mounted on a rigid sand-rooted support. Alternatively, Stainless steel sheet would be use as reflecting surface. The collector would be design using simple parabolic equations. From geometrical relations of the parabolic section, equations (1), the cross section for the parabolic concentrator would be trace as shown by figures.3.1. The sheet would be curve to form a parabolic dish module of reasonable length and aperture width with effective aperture area. The simple parabolic equation as stated by (NOVA, 2007) in line with equation (8) above.

The Receiver/Heat exchanger Design: The receiver is the part of the system that converts solar radiation to heat energy in a working fluid. The receiver consists of an absorber, heat exchanger and possibly heat storage.

Therefore, in this research work the heat exchanger would be inform of an improvise receiver in the form of a kettle-like form with an internal coil made from a good conducting material e.g. copper. It shall be used in conducting the steam generation test. The absorber would be in form of impinging surface for reflected solar radiation to strike. Radiation would be absorbed into the absorber material as heat. The heat exchanger transfers the energy to a working fluid that carries the energy out of the receiver. Equation (9) shows an energy balance for a receiver.

$$Q_{out} = Q_{abs} - Q_{loss} \tag{9}$$

Where
Q_{out} = useful energy transfer to working fluid
Q_{abs} = Energy received by the absorber
Q_{loss} = Receiver energy lost

The receiver design for this research work would act as an absorber, boiler, and heat storage unit. A cavity type absorber (receiver type) is selected due to its high absorption efficiency and low heat loss. Surrounding the absorber inside the receiver would contain 10 kg of sodium nitrate. This salt will acts as a heat transfer and storage media and 0.6 cm diameter copper tubing would be coiled through it. The working fluid is pumped through the tubing where heat is transferred to the fluid.

Collector supporting structure (Adjustable mechanism): For collectors' stability and accuracy, a rigid supporting structure would be designed, to structure the frame that would be supported for the rotation axis of the parabolic reflecting surface. It's used for the rotation of the horizontal axis for daily tracking of the sun. For test purpose and cost reduction, the unit would be designed for easy manual tracking system as shown Fig 5.

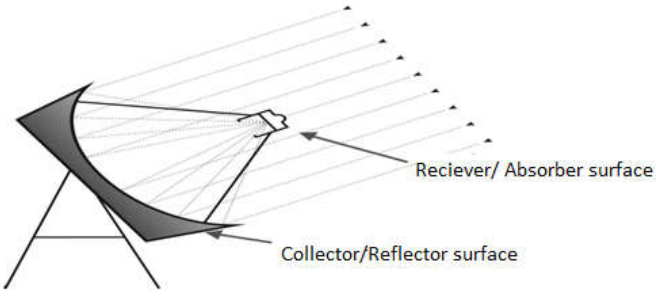

Fig 5. Adjustable Tracking System

Evaluation of Thermal Efficiency of the Collectors (η_{th})

The thermal efficiency of the collector (dish) (η_{th}) can be defined as the ratio of the useful energy delivered Q_U to the energy incident on the concentrator aperture Q_S (Gorjian et al, 2014):

$$\eta_{th} = Qu \big/ Qs \tag{10}$$

Assuming that the concentrator has an aperture area A_{ap} and receives solar radiation at the rate Q_S from the sun, the net solar heat transfer Q_s is proportional to A_{ap} and the direct normal insolation per unit of collector area I_b is given(Gorjian *et al*, 2014) as;

$$Q_S = I_b A_{ap} \tag{11}$$

Under steady state condition, the useful heat delivered by a solar collector system is equal to the energy absorbed by the heat transfer fluid Q_a, which is determined by the radiant solar energy falling on the absorber minus the direct or indirect heat losses Q_i from the absorber to the surrounding .i.e.

$$Q_u = Q_a - Q_l \tag{12}$$

Determination of Optical Efficiency of the Collector (H_o)

The optical efficiency 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. The equation to be used in deducing the optical efficiency given by (Gorjian *et al,* 2014) is:

$$\eta_o = \lambda\rho\tau\alpha\gamma\cos(\theta) \tag{13}$$

where λ is the un-shaded factor, ρ is the dish reflectance, $\tau\alpha$ is the transmittance-absorptance product, γ is the intercept factor of the absorber i.e. obstacle e.g, dust, birds e.t.c. θ is the angle of incidence.

The total heat lost by the absorber can be through the three basic heat transfers i.e. conductive heat loss (Q_{lk}), convection heat loss (Q_{lc}) and radiation heat loss (Q_{lr})

therefore; $Q_l = Q_{lk} + Q_{lc}\ \ Q_{lr}$

Evaluation of Instantaneous Efficiency of the Collector

Instantaneous thermal efficiency of a solar concentrator may be calculated from the energy balance on the absorber. If the useful thermal energy delivered by a concentrator is given by Garg and Prakash, (2000):

$$q_u = \eta_o I_b A_{ap} - u_L (T_{abs} - T_{a)} A_{abs} \tag{14}$$

then, the instantaneous thermal efficiency may be written as:

$$\eta = \frac{q_u}{I_b A_{ap}} = \eta_o - \frac{U_L (T_{abs} - T_a)}{I_b C} \tag{15}$$

where A_{ap} is the aperture area, q_u is useful thermal energy delivered, I_b is the beam radiation, T_{abs} is the absorber temperature, T_a is the ambient temperature, C is the concentrator ratio respectively, η_0 is optical efficiency and U_L is then overall heat loss coefficient.

At higher operating temperatures, the radiation loss term dominates the convection losses and the energy balance equations become (Ibrahim, 2012):

$$q_u = \eta_o I_b A_{ap} - U_L (T^4 - T_a^4) A_{abs} \tag{16}$$

where T is the temperature of heat transfer fluid entering/leaving the collector, while the U_L takes into account the accompanying convection and conduction losses, therefore, the instantaneous thermal efficiency η is given as(Garg and Prakash, 2000):

$$\eta = \eta_o - \frac{U_L (\mathrm{T}_{abs}^4 - \mathrm{T}_a^4)}{I_b C} \tag{17}$$

Since the absorber surface temperature is difficult to determine, it is convenient to express the efficiency in terms of the inlet fluid temperature by means of heat removal factor F_R defined by Ibrahim, (2012), as:

$$\eta = F_R \{\eta_o - \frac{U_L (\mathrm{T}_L - \mathrm{T}_a)}{I_b C}\} \tag{18}$$

where T_L is the overall temperature of the system.

The optical efficiency, heat loss coefficient and heat removal factor are dependent on the design parameters while the solar flux, inlet fluid temperature and the ambient temperature define the operating conditions. Therefore, the instantaneous thermal efficiency is dependent on two types of quantities, namely the concentrator design parameters and the parameters characterizing the operating conditions as shown in the equation.

Evaluation of Efficiency of the Receiver (Absorber)

Cooking occurs faster or at higher temperature, therefore, the heat lost is simply described by Adams and Allday (2000) as;

$$Q_{loss} = \frac{V \Delta T}{R} \tag{19}$$

where, ΔT is the difference between the initial and final temperature

R is the thermal resistance of the receiver,
V is the volume of the receiver, thus;
$Q_{loss} = \mu A\, \Delta T$

Note that, the thicker the walls of the receiver, the greater the value of the R, since

$\mu = \frac{conductivity}{thickness}$ i.e. the conductance (W/m^2) Therefore, the solar energy reflected upon the receiver per unit area can be calculated (Huseyin, 2004) as;
Energy = IVT

Where I is the Solar Insolation and V is the volume of the receiver and T is the time taken.

Therefore, the efficiency of the receiver can be deduced from specific heat capacity i.e. $IVT = MC\theta$ (heat exchange) equations as:

$$\eta = \frac{E_o}{E_i} = \frac{Q}{VIT} = \frac{M_{ex} C_{ex} + M_w \times C_w (T_{wf} - T_{wi}}{VIT} \tag{23}$$

Determination of Water Boiling Test (Wbt)

The PDSC performance can be analyzed using water boiling test method recommended by the Provisional International Standard for Comparison (Garba, *et al*, 1996). The methods include:

Water Boiling Test (WBT): it is a laboratory test that allows the researcher to be able to know the magnitude of heat utilized, thus:

$$H = \frac{\text{Total heat utilized}}{\text{Heat net supplied}} \times 100 \tag{24}$$

$$H = \frac{M_p C_p \times M_w C_w (T_i - T_o) M_v L_v}{A_c Q_c t} \times 100 \tag{25}$$

where,

M_w is the mass of the water,
M_p is the mass of the pot,
T_f and T_o is the change in temperature,
M_V is the mass of water evaporated,
L_V latent heat of vaporization of water,
C_W is specific heat capacity of water;
C_P is specific heat capacity of pot,
A is the area of the collector,
Q is the radiation intensity,
T is the duration.

Evaluation of Steam Generation Test

The performance of solar steam generating system can be evaluated by installing the necessary instrument to measure the required process parameters (Egbo, *et, al*, 2003). Thomas (1992) suggested that, the collector field efficiency η_{field} can be computed using the equation below;

$$\eta_{field} = \frac{mC_p (T_o - T_i)}{IA_c} \tag{26}$$

Where,

m is the collector fluid flow rate (kg/s),
C_p is the collector fluid specific heat capacity (kJ/kg/^{0}C),
T_0-T_i is the outlet and the inlet temperature (^{0}C),
I is the direct solar insolation,
A_c is the effective area of collector field (m^2)

EXPERIMENTAL PROCEDURE OR TEST

The components; the parabolic dish, receiver/heat exchanger and the support would be coupled together to form the Parabolic Dish Solar Concentrator System (PDSC). the performance evaluation of the PDSC system, experiments would be conducted for a given period of time on the performance of the receiver for steam generation and as well as for thermal applications (cooking application). The following parameters would be taken into account for the performance evaluation. First the availability of solar irradiation: this is measured using pyranometer instrument. Also ambient condition information like ambient temperature, ambient pressure/relative humidity, wind speed and its direction are essential for the performance calculation of PDSC.

Table 1 indicates the various parameters measured using the different relevant instruments. Below is a table showing the list of the apparatus used in recording the measurements taken during the experiment.

Table 1. List of instrument used in the measurement

S/N	Parameter measured	Instrument used
01	Solar insolation	Pyranometer
02	Wind speed	Anemometer
03	Relative density	Maximum and minimum
04	Ambient & content temp	Digital Data logger
05	Weight of water and other food substance	Electronic Weighing balance

Experimental testing facilities

To analyse the potential of the parabolic solar concentrating system, the following experimental test facilities would be developed, as schematically presented in Fig.4. Therefore, through these testing facilities, experimental tests would be carried out in order to evaluate the response and the efficiency of the system.

Expected results and analysis

The main expected results from this research work is to come up with improved and efficient system that can produce a higher temperature that is required for power steam generation use for domestic consumption.

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