Journal of Applied Mechanical Engineering
Yahuza et al., J Appl Mech Eng 2016, 5:4
DOI: 10.4172/2168-9873.1000212
Research Article
Open Access

Design, Construction and Testing of Parabolic Solar Oven

Yahuza I[1]*, Rufai YA[2] and Tanimu L[3]
[1]Department of Automobile Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria
[2]Kaduna Refining and Petrochemical Company Ltd, Kaduna, Nigeria
[3]Mechanical Engineering Department, Nuhu Bamalli Polytechnic Zaria, Nigeria

Abstract

The work is on the Design, Construction and Testing of Parabolic Solar Oven with focused reflector. Heat from the sun was concentrated on a transparent glass located at the focal point; to the black casted Aluminum plate (absorber) which was located in an enclosed insulated space (Oven). The heat was absorbed by the Aluminum plate which could be utilized for baking or cooking. The sun tracking was made to be manual tilt of the parabolic reflector and a booster was mounted on top of the Oven which would focus the sun rays into the enclosed oven through the top glass layer. The frame was made using 50 mm×3 mm angle iron. The holder and its support were constructed out of 3 mm×12 mm flat bar and shaped round to accommodate the receiver holder. The principles of heat transfer were carried out to ascertain the efficiency of the oven. The system was tested in average sunny/cloudy conditions; the test results gave a higher temperature of 104°C.

Keywords: Solar oven; Design; Solar energy

Introduction

Solar energy is one of the best ways of reducing the use of nonrenewable resources. With solar energy, the sun's rays are used to generate electricity, heat water or other fluids, charge battery, heat homes through glass windows and cook food. Usually a solar oven is used for cooking food which is used instead of firewood and other fuels to cook meals. One of the most famous solar ovens is the parabolic solar oven.

In a parabolic solar oven, the sun's rays are collected using a reflective surface like a parabola or curved surface. There are different types of parabolic solar ovens available which come with instructions on its creation. With a parabolic solar oven, it is possible to cook food at the same rate that food is cooked in conventional ovens [1].

The optical systems based on solar energy have been developed and implemented since 19th century. The maximum development of these systems was not until 1970 due to the global oil crisis, leading to the search for alternative sources of energy such as wind, bio-fuels, solar energy, etc. (Duffie and Beckman's, [2]. The idea behind a concentrating on solar collectors is to minimize the heat losses associated with solar collection. In many instances it is desirable to deliver energy at higher temperatures than those possible with flat solar collectors. A parabolic reflector concentrates incident solar radiation onto a much smaller receiver area, greatly decreasing heat loss and maximizing the available energy from the sun.

Concentrators can be reflecting or refracting, cylindrical, spherical, parabolic, and they can be continuous or segmented. Receivers can be convex, flat, cylindrical, covered and uncovered. Because of complexity and very wide scope of concentrators and concentrator designs, it is difficult to find developed general analyses of each specific type of concentrator. Therefore each solar concentrator design must be studied on a per case basis Duffie [2].

Characteristics of the Relative Movement of the sun

In the Design of thermal systems based on solar power, the coordinates of the sun in relation to the collector during the day, with the aim of catching maximum solar radiation, must be considered. The description of some relevant terminologies related to sun parameter will be enormous; which include Azimuth angle, solar elevation angle, Zenith angle, and Hour angle.

Azimuth angles

The azimuth angle is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north southern hemisphere. The azimuth angle varies throughout the day. At the equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thus making the azimuth angle 90^0 at sunrise and 27^0 at sunset. In general, however, the azimuth angle varies with the latitude and time of year.

The azimuth angle is like a compass direction with North = 0^0 and south = 180^0.

The solar azimuth angle is the azimuth angle of the sun. It is must often defined as the angle from due north in a clockwise direction Figure 1.

Solar elevation angle

Sun light, sun angle, solar latitude angle or elevation (gs) is the angle between the line that points from the site towards the centre of the sun and the horizontal.

Zenith angle

The zenith angle is the opposite angle to the sun height (90° – gS). At a sun height of 90°, the sun is at the zenith and the zenith angle is therefore zero Figure 2.

Declination angle (δ) The declination angle denoted by δ, varies seasoning due to the tilt of the earth on its axis of rotation and

***Corresponding author:** Yahuza I, Department of Automobile Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria, Tel: +234 818 071 4594; E-mail: ibnyahuza@yahoo.com

Received March 26, 2016; **Accepted** April 29, 2016; **Published** May 03, 2016

Citation: Yahuza I, Rufai YA, Tanimu L (2016) Design, Construction and Testing of Parabolic Solar Oven. J Appl Mech Eng 5: 212. doi:10.4172/2168-9873.1000212

Citation: Yahuza I, Rufai YA, Tanimu L (2016) Design, Construction and Testing of Parabolic Solar Oven. J Appl Mech Eng 5: 212. doi:10.4172/2168-9873.1000212

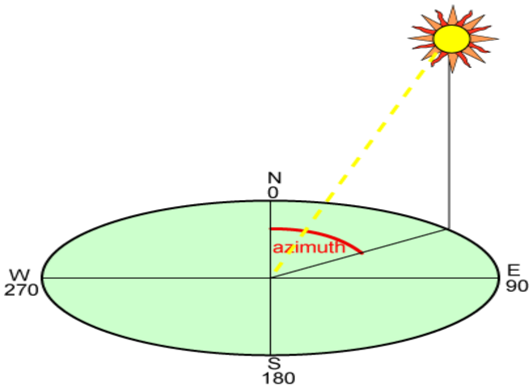

Figure 1: Solar azimuth angle.

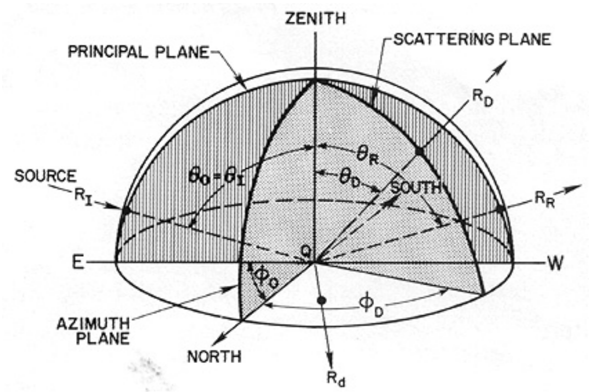

Figure 2: The zenith angle.

the rotation of the earth around the sun. If the sun were not tilted on the axis of rotation, the declination would always be 0^0. However the earth is tilted by 23.45^0 and the declination angle varies plus or minus this amount. Only at the spring and fall equinox is the declination angle equal to 0^0 the declination of the sun is the angle between the equator and the line drawn from the centre of the earth to the centre of the sun. The declination is zero at the equinoxes (March 22 and September 22) positive during the northern hemisphere summer and negative during the northern hemisphere winter. The declination reaches a maximum of 23.45^0 and June 22 (summer solstice in the northern hemisphere) and a minimum of -23.45^0 on December 22 (winter solstice on the northern hemisphere) [3].

The Earth-sun Parameters

This is the angle of the equatorial plane of the earth relative to its orbital plane around the sun. This changes according to where the earth is in its orbit round the sun.

ω=The hour angle which is the stage of the earth's rotation relative to solar noon. It is when the meridian on which our point is located facing the sun, at that time the sun is at its highest point in the sky. The earth rotates around its, has the hour angle at 10.00 (solar noon minutes two hour) solar time is 30 degrees and at 13.00 (solar noon plus one hour) it in +15 degrees.

Hour angles

Viewed from above North Pole, the earth is rotating anti-clockwise around its axis. The hour angle defines the point in the rotation relative to solar noon. The earth rotates through 360 degrees in 24-hours. Thus it is rotating at the rate of 15 degrees per hour. At 09:00 solar-time, solar noon is three hour away, thus this hour angle is 45 degrees. By correction angles in advance of solar noon are negative after it possible.

Materials and Methods

Selection of materials

The selection of materials includes the following four fundamental factors:

1. Availability of material;
2. Suitability of material for the working condition in service;
3. The cost of material; and
4. The properties of a material

The following materials were used to construct the Parabolic Solar Oven:

- Mild Steel
- Silver mirror
- Pyrex Glass
- Foil paper
- Solid Foam
- Aluminum

The Table 1 below described properties and choice of materials in preference to application area.

Design calculations

The design procedures of various parts of the system with their detail explanation below;

Determination of parabolic reflector's base parameters

The dimensions of a symmetrical parabola are related by equation [4]

$$h = \frac{R_{rim}^2}{4f} \quad (1)$$

Where f = *focal length*, R_{rim} = *the rim* radius and *P=Parabola depth*

The focal distance is given by

$$f = \frac{D_{ap}^2}{16h} \quad (2)$$

Assuming the aperture diameter to be 0.8m and 0.105m depth

Where, D_{ap} = aperture diameter, h= the dept, D_{ap} =0.8 m and h=0.105

$$f = \frac{(0.8)^2}{16(0.105)} = \frac{0.64}{1.68} = 0.381m$$

The relationship between focal length with the rim angle and aperture diameter of the parabolic dish is given (Stine, William B. Diver, Richard B. 1994):

$$\phi_{rim} = \tan^{-1}\left(\frac{8f/D_{ap}}{16\left(f/D_{ap}\right)^2 - 1}\right) \quad (3)$$

Where φ_{rim} = *Rim angle*

S/No	Material	Properties	Remark
1.	Mild Steel	It is ductile & malleable. It is tough and can be hardened and tempered. Carbon content of 0.08-0.35% and melting point is 140^{0}C. It has strength and can absorb shocks It can be readily forged and welded. Used for all kind of structural work in bridges and buildings, graders, rails, angle iron etc. It's also used for rivets, bolts, wire-tapes and for making sheets.	Mild steel sheet was used for the Parabolic reflector base, guard & Boaster base. Mild Steel angle iron was used for the entire frame.
2.	Glass mirror	High reflectance/transmittance and optical performance compared with other reflective materials (Aluminum & silver mirror 82-98% reflectance) Resistance to degradation, good secularity [≤ 2mrad (0.10 degree)], durability and resistance to distortion from loads. High density and brittle Mirrors are used mostly in such solar thermal systems/subsystems as parabolic troughs, parabolic dishes, spherical bowls, and heliostats. Glass mirrors are used for domestic and decorative applications.	A glass mirror was used for the reflector (Parabolic).
3.	White glass	It has very low solar absorptivity hence it's transparent and mostly colorless in nature. However, the solar absorptivity of glass is dependent of thickness and chemical content of the glass. Solar absorptivity is 0.01-0.12% and reflectivity of 0.1-0.25%. The greater percent of solar radiation is reflected off the glass. (0.1-0.25% reflection).Glass usually not losing 20% solar radiation that leaves more than 80% of the sunlight that gets transmitted. Used in kitchen utensils and laboratory wares (borosilicate glasses)	It is used for construction of the Oven.
4.	Foil Paper	Thickness of about 0.00017 in. to a maximum of about 0.0059 in. (aluminum 0.006 in. is sheet). It has **excellent** and **good** compatibility. Impermeability to water vapor and gases. Good thermal insulation and reflection. Aluminum foil paper is widely used for thermal insulation, heat exchangers and cable liners.	It is used in the wall surface of the Oven and Boaster.
5.	Foam	Thin lightness and compressibility. Ability to be reshaped repeatedly when heated above a certain temperature and cooled. Low density hence has a very high strength-to-weight ratio. Solid foam is used for thermal insulation and flotation devices. It is used as packing materials and stuffing's. Used for dynamic structural support.	Solid Foam was used for Oven as insulator between the inner and outer shells.
6.	Aluminum	Aluminium is ductile and malleable. High resistance to corrosion. Specific gravity, melting and boiling point are 2.7, 658^{0}C and 2057^{0}C respectively. It is good conductor of heat and electricity. It is tensile varies from 95-157MN/m^2. Aluminium employed in the manufacture of furniture, rail road/trolley cars, automobile parts, electric cables/bus bars, rivets, kitchen utensils and collapsible tubes for pastes. It is as a protective coat for metals.	Used for the absorber plate

Table 1: Material selection.

$$\phi_{rim} = \tan^{-1}\left(\frac{8\times 0.38/0.8}{16\left(0.38/0.8\right)^2 - 1}\right) = \tan^{-1}\left(\frac{3.04/0.8}{16\left(0.1444/0.640\right) - 1}\right)$$

$$= \tan^{-1}\left(\frac{3.04/0.8}{\left(2.31/0.64\right) - 1}\right) = \tan^{-1}\left(\frac{3.80}{2.61}\right) = \tan^{-1} 1.4559 = 55^\circ$$

To calculate the aperture opening area:

$$A_{ap} = \frac{\pi D_{ap}}{4} \tag{4}$$

$$= \frac{3.142\times 0.8^2}{4} = \frac{3.142\times 0.64}{4} = \frac{2.011}{4} = 0.536 m^2$$

Diameter of the concentrator along its surface D_s, can be determine; the distance from the rim along the surface to the vertex, then back along the surface to the rim. This is sometimes called "linear diameter" of the parabola, and is useful in determining the size of the material need to makes it. It is the diameter of a flat, circular sheet of material, usually metal sheet, which is right size to be cut and bent.

Determination of surface area of the parabola is then given by [4].

$$A_s = \frac{8\pi}{3} f^2 \left[\left[\left(1 + \left(\frac{D_{ap}}{4f}\right)^2\right)\right]^{3/2} - 1\right] \tag{5}$$

Where D_{ap} = the aperture diameter and f = the focal distance

$$= \left(\frac{8\times 3.142}{3}\right)\times\left(0.381^2\right)\left[\left[\left(1 + \left(\frac{0.8}{4\times 0.381}\right)^2\right)\right]^{3/2} - 1\right] = \left(\frac{25.132}{3}\right)\times(0.145)\left[\left[\left(1 + \left(\frac{0.8}{1.524}\right)^2\right)^{3/2}\right]\right] = 1.039 m^2$$

The volume of the parabola also can be determined Tables 2 and 3:

$$V_C = \frac{1}{2}\pi R_{rim}^2 h \tag{6}$$

$$= \frac{1}{2}\times 3.142\times 0.4^2\times 0.105 = 0.0264 m^3$$

The surface area of imaginary sphere is given by Folaranmi [5]

$A_s = 4\pi r_s^2$ 3.23, $A_E = \pi r_E^2$ 3.24

If average distance of the sun from earth =1.5 × 10^8 km

Consider a sphere of radius 1.5 × 10^8 km with the sun at it centre.

Let A_S = Surface area of this imaginary sphere, A_E = Cross sectional area of the earth

r_s = radius of the sphere, r_E = radius of the earth

Where r_E = 6.4 × 10^6 km, r_s = 1.5 × 10^{11} km

$$A_E = \pi r_E^2 = 3.142\left(6.4\times 10^6\right)^2 = 1.287\times 10^{11} m^2$$

$$A_s = 4r_s^2 = 4\times 3.142\left(1.5\times 10^{11}\right)^2 = 2.828\times 10^{23} m^2$$

Percentage of Sun's output = $\left[\left(A_E/A_S\right)\times 100\right]$ 3.25 $= 0000000455\%$

This means that the earth received 0.00000000455% of sun's energy output.

The world's average annual energy consumption is 9.262 × 10^{23}kW.

Parabolic Reflector	
Aperture diameter of the parabolic reflector	0.8 m
Aperture Area of the parabola	0.536 m^2
Surface area of the reflector	1.04 m^2
Depth of the parabola	0.105 m
Focal length	0.384 m
Rim angle	55^0

Table 2: Parameters of the parabolic reflector.

Parameters of the Oven	
Internal diameter of the Oven	0.49 m
Outside diameter of the Oven	0.39 m
Internal Surface area of the Oven	0.884 m2
External curve surface area	1.2 mm
Volume of the Oven	0.034 m3
Concentration ratio	5.5

Table 3: Parameters of the oven.

The extraterrestrial solar radiation in Nigeria can be calculated as given by (Folaranmi2009).

$R_X = I_{XC}\ A_{cL}$ 3.26, R_x = extraterrestrial radiation, A_{CL} = continental area, I_{XC} = solar constant

I_{XC} = 1353kWh, A_{CL} = 932768x10^6

R_X= 1353 × 9328 ×10^6= 1.262 × 10^{15} W/m^2

Therefore, for a yearly average sunshine hour of 9 hours/day

= 1262 × 10^{15} × (366×9) =4.157× 10^{18} Wh/year

Assuming a clearness index of 50% since 47% of extraterrestrial radiation reaches the earth surface. Terrestrial radiation in Nigeria land area (Folaranmi2009)

= [(50/100) ×4.157 ×10^{18}] = 2.079 × 10^{18} Wh/year

To calculate the direct radiation reaching the earth surface as a function of time of the day (t), for location (γ) with the sun at declination angle (δ)

Let Z -zenith angle, γ -Latitude of location, δ-declination angle, t-hour angle of the sun

I_z- direct solar radiation, I_{XC}-extraterrestrial solar radiation constant, I_h-horizontal radiation

x and c are climate-graphical determined constants. The Zenith angle is given by:

$$\cos z = \sin\gamma \sin\delta + \cos\gamma \cos\delta \cos t \quad 3.27 \quad = \sin 14^0 \sin 0 + \cos 14^0 \cos 0^0 \cos 0^0$$

= 0.2192 × 0 + 0.970291×1

= 0.97029

Z=cos^{-1}(0.97029) = 14°

The intensity of the solar radiation after passing through the atmosphere is calculated;

$$I_Z = I_{XC} e^{C(\sec z)X} = 1353 e^{-0.357(1/\cos 14)0.678} \quad (7)$$

$$I_Z = I_{XC} e^{C(\sec z)X} = 1353 e^{-0.357(1/\cos 14)0.678} = 940 w/m^2$$

This is the value of the direct radiation on a normal surface and it is the maximum value possible. In practice only systems using full tracking mechanisms can collect this radiation.

The value of radiation on horizontal surface is given;

$I_h \cos z$= 940 × 0.9702957= 912 w/m^2

Energy balance

The expected power of the parabolic reflector is given by:

$Q_{C=} I_{XC} A_{ap} \rho$ Where ρ = reflectance of the mirror = 0.98

I=1353kwh, A_{ap}= 0.536 m^2, Q_c =1353 × 0.536 × 0.98= 710W

The heat transferred into the Oven is estimated by:

$$Q_{ov} = Q_{in} - Q_{ref} - (Q_{cond} + Q_{conv} + Q_{rad.em}) \quad (8)$$

Where the beam radiation Q_{in} entering the enclosed Oven is given by:

$Q_{in} = I_{xc} A_{ap} \rho \phi$

Where ρ = surface reflectance, φ = interception factor

The radiation reflected back from the enclosed Oven is calculated as (Duffi and Beckman, 2006).

$$Q_{ref} = (1-\alpha_{eff})\ Q_{in} \quad (9)$$

Where α_{eff} is the effective absorbance of the cavity of the oven and is defined:

$$\alpha_{eff} \frac{\alpha_{in}}{\alpha_{eff} + (1-\alpha_{in})(A_{ap}/A_{in})}$$

The conduction heat losses through the insulation are dissipated as;

$$Q_{con} = \frac{T_{abs} - T_{amb}}{\frac{L_{in}}{k_{in}} + \frac{1}{h_{out} A_{in}}}$$

Construction and assembly of the components

This is to describe the detailed construction procedure of the Parabolic Solar Oven. It consist of three section; the Oven, the Frame and Parabolic Reflector. The construction of the Parabolic Solar Oven, based on the initial design sketches, materials were brought, in which the detail explanation are given as follow:

Mild Steel sheet of 2mm thick, 584mm width and 813mm length (× 2 sheets) was used to construct the outer and inner wall layers of the Oven, while solid foam of thickness 50mm by 1580mm length was used as an insulator to fill the gap between the inner and outer layer of the Oven. The inner wall also was lagged with Aluminum foil paper; all are preventing loss of the solar heat absorbed inside the Oven. White glasses (2 pieces) of Ø530mm x 4mm thickness were fixed to cover both the top and bottom of the Oven.

The frame of the system was to be made with Mild steel angle iron (two lengths) 4 mm × 38 mm × 4270 mm per length. The frame was incorporated with a guard made with mild steel sheet 660 mm × 580 mm × 2 mm thickness, a boaster plate thickness 2 mm × 300 × 540 mm and a mild steel shaft Ø20 mm × 1220 mm length.

A parabolic dish with aperture diameter 800mm was used as the solar collector bas where broken mirrors were glued, focal length 380 mm i.e., the solar collector. An Aluminium absorber plate Ø250 mm × 20 mm thickness painted black was placed inside the Oven when baking. The base of frame carries three tires each Ø100 mm, for easier movement or positioning of the system [6-12].

Construction of parabolic reflector

A Parabolic dish was used as the reflector based where a glass

Time	9:30 am	10:30 am	11:30 am	12:30 pm	1:30 pm	2:30 pm	3:30 pm
Day	T_1-T_2	T_1-T_2	T_1-T_2	T_1-T_2	T_1-T_2	T_1-T_2	T_1-T_2
1	26 -37	30-43	29-41	30-44	29-63	27-61	25-59
2	27-39	29-35	30-53	31-77	30-67	26-53	28-61
3	28-41	29-55	30-67	31-79	29-73	29-67	27-61
4	28-37	29-72	30-78	31-82	31-85	28-77	27-66
5	29-34	30-74	30-84	30-90	31-97	31-95	30-83
6	27-44	30-74	35-97	34-104	38-99	31-96	28-87

Table 4: Results.

mirror was cut into 0.05m² pieces and glued onto the interior surface of the dish.

Construction of the oven

The components of the Oven include:

(i) Outer/inner layers (ii) Door inner/outer layers (iii) Bottom/Top Covers

A Mild Steel sheet metal 2 mm thickness was bought, following the design specifications, the material was marked with marking-out tools (scriber, steel rule, dot punch, divider etc.). After it was marked and brought out the patterns, all unwanted material were cut out with chisel and shear [13-18].

The Oven inner/outer layer, Door inner/outer layer were rolled with rolling Machine and formed cylindrical/semi-cylindrical shapes according to their specification. An Arc Welding Machine was used to weld the edges joints of the layers.

The bottom/top covers was constructed too with sheet metal; the material was marked (round) with marking tool i.e., divider, dot punch and divider. The outside diameter was first marked then the inside. After marked successfully, followed the inside mark and cut off which form washer/ring like.

Construction of frame

A Mild Steel angle iron was bought and brought into the workshop, measured and cut (used tape rule, scriber, bench vice and hack saw) according to the specification of each structural component member. When it was cut then used file and hand grinding machine to filed and adjusted where necessary. The frame structural members were joined with electric arc welding process.

Assembly

The entire components of parabolic solar Oven were mounted on the frame after construction. Firstly the oven was mounted on the upper part of the frame with aid of bolt and nut followed by the parabolic reflector which was hinged on a beam shaft located below the reflector, lastly the booster shield was fastened on the frame too; located at upper back the Oven as shown in exploded diagram Figure 3 and Table 4.

Conclusion

Based on the results obtained during the test of the oven, the enclosed Oven temperature (highest) reading was 104°C against 34°C ambient temperature. The temperature however varies with time and weather condition. There are some reading with the same ambient temperature but differs in the actual oven temperature, it was due to the tracking problem.

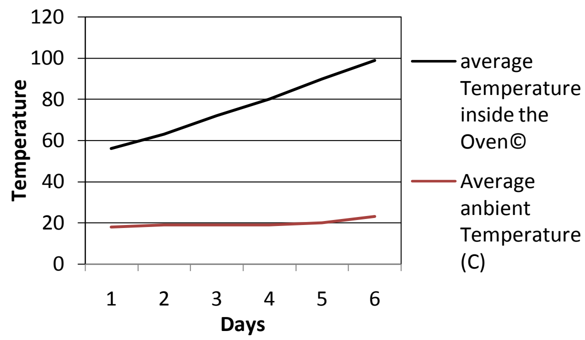

Figure 3: Average temperatures.

References

1. Solar Cooker International network (History of Solar Cooking).
2. Duffie JA, Beckmans WA (2006) Solar engineering (3rdedn) Wikey Press. Journal of physics: Comference Series.
3. Pidwirny M (2006) Earth-Sun Geometry. Fundamental of physical Geography.
4. El Quedermi AR, Ben Saleh M, Askri F, Ben Narallah M, Aloui F(2009) Experimental study of a parabolic solar concentrator. Revue des Energies Reneuvelables 12: 395-404.
5. Folaranmi J (2009) Design construction and testing of a parabolic solar steam generator. Leonardo Electronic J Practices and Technologies: 115-133.
6. Aliyu MK, Gambo D, Shehu B (2014) Nubapoly Journal of Engineering Research (NUPJER).
7. John D, Beckman W (1991) Solar Engineering of thermal Process (2ndedn) New York: John wikey and Sons Inc.
8. Eames PC, ZackaroPoulos A, Mclarnon D, Norton B(1999) An experimental procedure to determine solar energy flux distributions on the absorber of line-axis compound parabolic concentrators. Renewable Energy 16: 761-764.
9. Kirchhoff G (1896) Radiation between the radiating and absorbing powers of different bodies for light and heat. Translated by F Guthrie in phil mag series 4: 130.
10. Jordan RC, Ibele WE (1995) Mechanical engineering from solar energy. Stanford Institute Mentopark.
11. Kasten, Young (1989) Air mass plane parallel model/empirical formula.
12. Kongtragool B, Wongwises S (2005) Modeling generation systems from using solar stirling engines parabolic dish. International J Renewable Energy 43: 1-7.
13. Aalfs M (2002) Solar cookers. International Principle of Solar Oven.
14. National Renewable Energy Laboratory (NREL) Student resources on concentrating solar power.
15. Baltan R, Velazquez N, Cota Espericueta A, Sauceda D, Perez G (2012) Mathematical model for the study and design of a solar dish collector with cavity receiver for it application in Stirling Engines. J Mechanical Science and Technology 26: 3311-3321.
16. Solar Oven Development and Testing Project Florida Solar Energy Project Solar Ovens Society (SOS).
17. Sunrise Sunset or Sun position for any location.
18. (1985)Technical Information Branch Solar Energy Research Institute Colorado Silver/Glass Solar Mirrors for Solar Thermal Systems.