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Full Length Research Paper

Design analysis of solar bi-focal collectors

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This study carried out the design analysis of solar bi-focal collectors with the basic units comprising the paraboloid concentrators, receivers and support/connectors. The design of the receivers is such that it works on thermo-siphon principle while the heat energy requirement for each receiver is 650 kJ. Solar energy required to provide the needed power input in the collector's receiver is amounted to 0.967 kJ/s. The results of the analysis revealed that each collector has diameter of the receiver of 0.3 m, aperture diameter of 1.4 m and internal surface area of 1.53 m^2. The materials and dimensions of parts were selected based on the design specifications. The design analysis will serves as basis for the development of a solar tracking bi-focal collector system for possible steam generation.

Key words: Solar, collector, concentrator, receiver, heat energy.

INTRODUCTION

Solar radiation has been identified as the largest renewable resource on earth (Muller-Steinhagen, 2003). The maximum intensity of solar radiation at the earth's surface is about 1.2 kW/m^2 but it is encountered only near the equator on clear days at noon. Under these ideal conditions, the total energy received is from 6 to 8 kWh/m^2 per day (Androsky, 1973; Spillman et al., 1979; Halacy, 1980). Solar energy can be captured in different ways; also many different methods for collecting the solar energy from incident radiation are available. Solar thermal power devices use the sun rays to heat fluid, from which heat transfer system may be used to produce steam. The steam in turn is converted into mechanical energy in a turbine and into electricity from a conventional generator coupled to the turbine (Eastop and Mc Conkey, 1993).

Paraboloidal concentrators have the ability to raise various absorbers and working fluids to high temperatures. Broman and Broman (1996) noted that the concentration factors needed for temperatures of several 100°C were obtained easily with parabolic troughs if the mirrors were made with high precision. They also observed that if one chooses a dish-type mirror that concentrates the light onto a focal spot instead of a focal line, there is a rather large freedom to appropriate the parabolic surface and still obtain the desired concentration ratio. The maximum concentration factor and temperature attainable in practice depends on the aperture size, reflectivity and accuracy of the surface contour, and the degree to which the concentrator approximates a true paraboloidal geometry (Ong, 1974). The basic objective of this study is to design solar bi-focal collectors that can heat water for continuous production of steam at a temperature above 100°C.

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MATERIALS AND METHODS

Energy calculation in order to determine the heat energy required to generate steam at the required temperature in the receiver was carried out using the formulae (Abbott, 1977; Sayigh, 1977):

$$Q = M_w C_w \Delta\theta \quad (1a)$$

$$\text{Power} = \text{Energy} / \text{Time}, \quad (1b)$$

Where Q is the heat energy (J), M_w is the mass of fluid, C_w is the specific heat of fluid (kJ/kg.K) and Δθ is change in temperature.

Determination of solar energy required to provide the needed power input in the collector's receiver using expression given by Sayigh (1977) is:

$$Ei = \tfrac{1}{4} \pi D^2 \times Ha \quad (2)$$

Where Ei is the solar energy, D is paraboloid aperture diameter (m), Ha is intensity of direct solar radiation (W/m^2).

Calculation of collector design parameters and component parts material selections can be done using the following equations (Backhouse et al., 1962; Sayigh, 1977; Stroud, 1988).

Aperture diameter; $D = \sqrt{\frac{4E_{i1}}{\pi H_a}}$ (3)

Equation of a parabola, $x^2 = 4fy$ (4)

Where x and y are coordinates of the points along the curve of the parabola and f is the focal length.

Internal surface area of the parboloid,

$$A_p = \int_{y_1}^{y_2} 2\pi \left[1 + \left(\frac{dx}{dy}\right)^2\right]^{\frac{1}{2}} dy \quad (5)$$

Concentration ratio, $CR = \left(\frac{D}{d}\right)^2$ (6)

Where d is the receiver diameter (m)

Focal length, $f = \frac{D(1+\cos\emptyset)}{4\cos\emptyset}$ (7)

Where ø is the rim half angle

Depth of the dish, $h = f - \frac{D}{2}\cot\emptyset_{opt}$ (8)

Where $ø_{opt}$ is the optimum rim angle

The Length of the arc of the Parabola,

$$S = \int_{x_1}^{x_2} \left[1 + \left(\frac{dy}{dx}\right)^2\right]^{\frac{1}{2}} \quad (9)$$

Determination of the (x, y) coordinates of the points along the curve of the parabola was done by employing parabola calculator version 2.0 program developed by Mike (Light Concentrated From Below, 2004).

Receivers' support design was carried out using the formulae given by Khurmi and Gupta (2004): The Euler formula for the crippling or buckling load W_{cr}:

$$W_{cr} = \frac{\pi^2 EI}{L^2} \quad (10)$$

Where E is Modulus of elasticity (N/m^2), I is moment of inertial (kg.m^2) and L is equivalent length of column (m).

The Rankine's formula is expressed as:

$$W_{cr} = \frac{\sigma c \times A}{1 + a\left[\frac{L}{K}\right]^2} \quad (11)$$

Where σ_c is crushing stress or yield stress in compression, a is Rankine's constant, A is area of cross section (m^2), L is equivalent length of column (m), and K is least radius of gyration

RESULTS AND DISCUSSION

Design consideration

For this study, bi-focal solar collector system is conceived for possible generation of steam. Maiduguri, a semi-arid area, located on latitude 11.85° north and longitude 13.08° east with altitude of 354 m and annual mean daily global solar radiation on a horizontal surface of 6.176 kWh/m^2-day (Layi Fagbenle, 1990; Gisilanbe, 1995; Onyegegbu, 1993; Onyegegbu, 2003) has been chosen as the study area. The inlet water temperature to the first collector is taken as 35°C, an overall mean monthly maximum temperature over a period of 7 years for Maiduguri (NIMET, 2003).

Energy calculation

Heat energy required to generate steam at a temperature above 100°C should be useful energy delivered to the working fluid in the absorbers. In order to estimate the required heat energy, the following computation was carried out based on the assumptions that:

1) The first collector is expected to generate steam at a temperature of 100°C from inlet water temperature of 35°C.
2) The second collector is to raise steam temperature from 100 to 235°C.
3) The absorbers are of flat metal plate with arrangement for circulating water pass through a continuous tube bent in a sinusoidal shape fastened to the flat plate facing the reflectors.

For this study, the capacity of the first collector absorber pipe was taken as 0.25 x 10^{-3} m^3 made of 15 mm diameter and 1 mm thick galvanised iron because of its ability to withstand high temperature and pressure. The main water way to the receiver is a 15 mm galvanised iron pipe from the centre of the reflector along the focal line. A parallel pipe conveys heated water to the second collector system. The design of the receivers is such that they work on thermo-siphon principle. The flat plate receivers' diameters on which the absorbers are fixed are taken as 0.3 m.

The receiver (Figure 1) is made up of flat plate of mild steel sheet of 1 mm thickness and 0.3 m diameters, galvanised iron absorber pipe of 15 mm diameter and 1.414 m length in coil form, mild steel sheet of 1 mm thickness to serve as cylindrical part enclosure, insulator of 20 mm thickness behind the plate, insulator lagging from mild steel sheet of 1 mm thickness, and glass cover

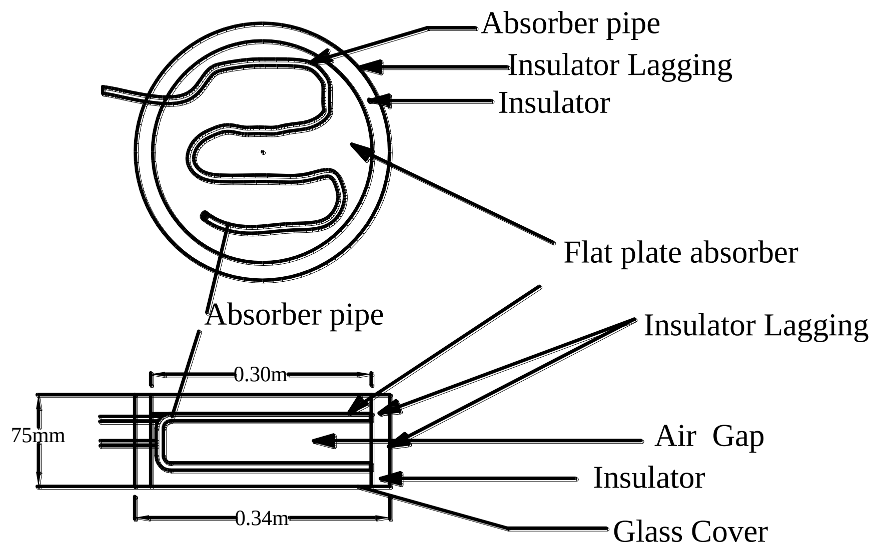

Figure 1. Receiver's components.

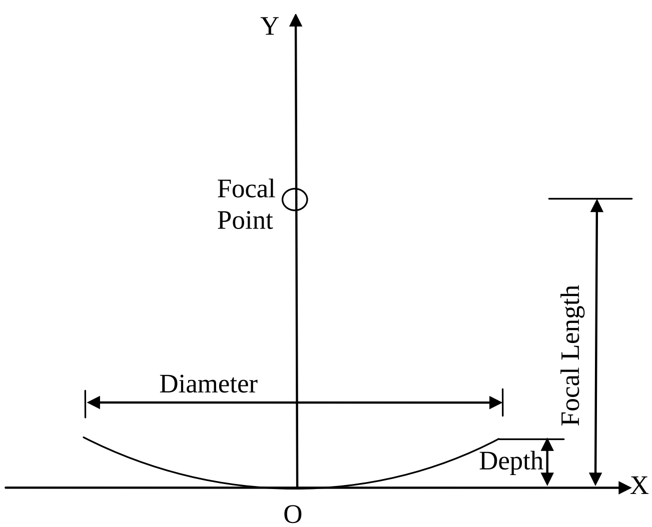

Figure 2. Parabola curve and coordinates
x -700.00, y 145.00; x -612.50, y 111.02; x -525.00, y 81.56; x -437.50, y 56.64; x -350.00, y 36.25; x -262.50, y 20.39; x -175.00, y 9.06; x -87.50, y 2.27; x 0.00, y 0.00; x 87.50, y 2.27; x 175.00, y 9.06; x 262.50, y 20.39; x 350.00, y 36.25; x 437.50, y 56.64; x 525.00, y 81.56; x 612.50, y 111.02; x 700.00, y 145.00.

over the absorber leaving an air gap of about 50 mm. Input values used for some quantities are as follows:

Inlet water temperature to the first collector, T_w = 35°C
Density of water, ρ_w = 1000 kg/m^3
Specific heat capacity of water at 35°C, C_w = 4.179 kJ/kg.K
Specific latent heat of steam, L_s = 2260 kJ/kg
Specific heat capacity of steam at 235°C, C_{s1} = 3.69 kJ/kg.K
Specific heat capacity of galvanised iron, $C_{G.I}$ = 0.473 kJ/kg.K
Density of galvanised iron, $\rho_{G.I.}$ = 7, 801 kg/m^3

Design results

A) Heat energy required to convert 0.25 x 10^{-3} m^3 of water at 35°C to steam at 100°C in the absorber of the first collector was calculated to be 650 kJ
B) Power input required, P_1 if heat energy of 650 kJ is to be made available in the absorber under 15 min (resident period) is 0.722 kJ/s
C) Solar energy required to provide the needed power input in the collector's receiver, E_{i1} is 0.967 kJ/s.
D) Dimension of the collectors.

For this design, the dimensions of the first and second collector are the same. These are
1) Aperture diameter of the paraboloid, D = 1.4 m
2) Focal length of the paraboloid, f = 0.8428 m
3) Diameter of the receiver, d = 0.3 m
4) Concentration ratio of the paraboloid, CR = 22
5) Length of the Latus rectum, LR = 3.3712 m
6) Internal surface area of the paraboloid, Ap = 1.53 m^2
7) Length of arc of the parabola, S=0.73 m

E) The (x, y) coordinates of the points along the curve of the parabola are as follows and the schematic diagram is shown in Figure 2.

Material selection and specifications

1) Flat sheet metal of 0.5 mm thickness was selected for the shell (Figure 3),

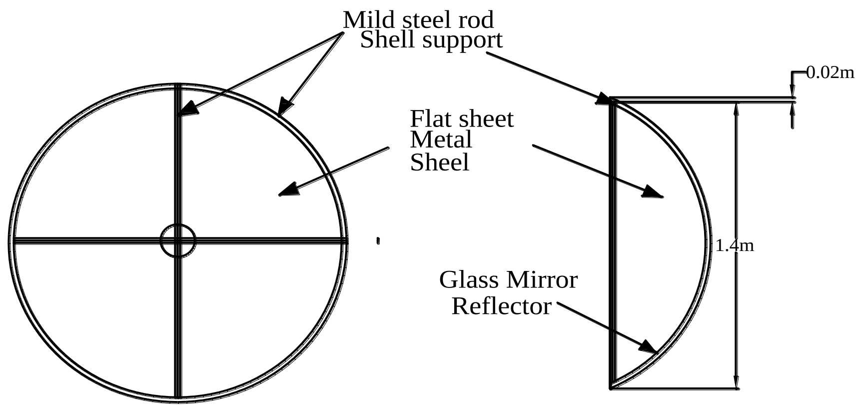

Figure 3. Paraboliod concentrator components.

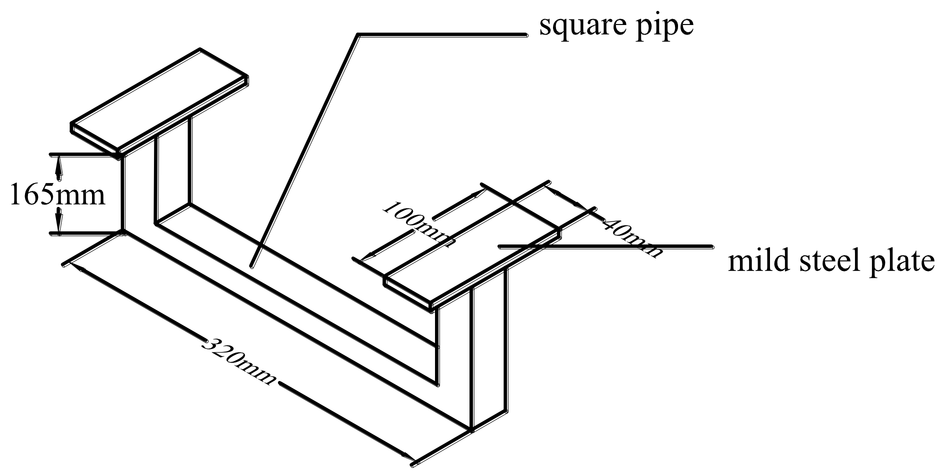

Figure 4. Hinge support.

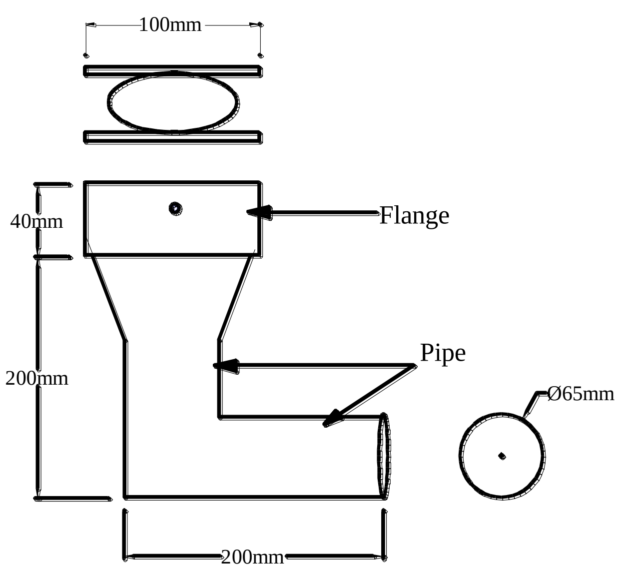

Figure 5. Connector for concentrator to the rotating support.

2) Mild steel rod of 4 mm radius was selected for the shell's support (Figure 3)
3) Glass mirrors reflector (Figure 3) of 3 mm thickness was selected for the reflective surface of the concentrators with a total area of 1.53 m^2.
4) Hinge/support for positioning collector relative to the axis of rotating support (Figure 4). Two numbers mild steel bar of 3 mm thickness, 100 mm length and 40 mm breath to be joined with 40 mm square pipe of 0.65 m length and thickness of 1 mm was selected.
5) Connector for the concentrator to the rotating support (Figure 5) is made up of mild steel pipe of internal diameter 65 mm, 2 mm thickness and length of 0.2 m, and edge flanges (4 numbers) of mild steel flat bar of 3 mm thickness, length of 100 mm and breath of 40 mm.
6) Receiver support

For proper support and stability, three number supports were selected for the receiver (Figure 6). The supports are to be equally spaced and connected between

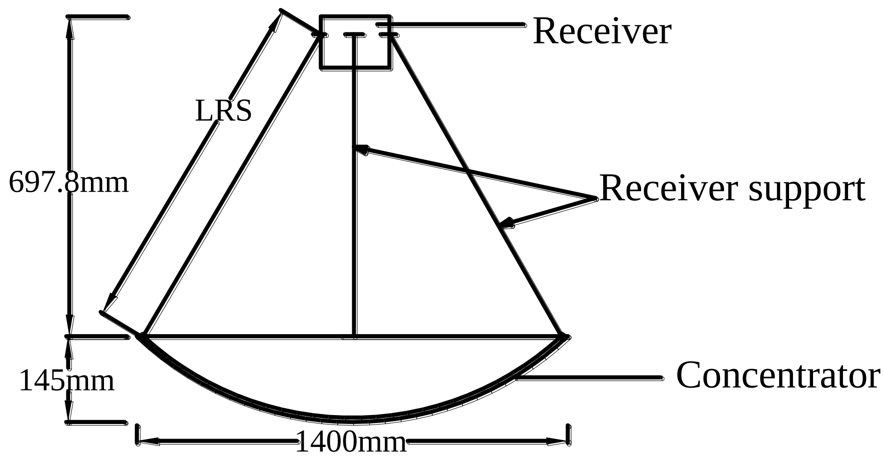

Figure 6. Receiver's support arrangement.

Table 1. Paraboloid concentrator components specifications.

S/No.	Component description	Material specification	Quantity	Mass (kg)
1.	Shell	Mild steel 0.5 mm thickness	1.53 m^2	5.28
2.	Shell support	Mild steel rod of 8 mm diameter	20.866 m	4.10
3.	Hinge/support	Mild steel flat bar of 3 mm thickness and 40 mm breath	0.2 m	0.18
		Square pipe of 40 mm square and thickness 1 mm.	0.65 m	0.23
4.	Connector	Mild steel pipe of 65mm internal diameter and 2 mm thickness	0.2 m	0.63
5.	Reflector	Mild steel flat bar of 3 mm thickness and 40 mm breath	0.3 m	0.9
		Back-silvered glass mirrors of 3 mm thickness	1.53 m^2	11.38
6.	Other: Bolts and nuts screw	Mild steel	Lot	0.5

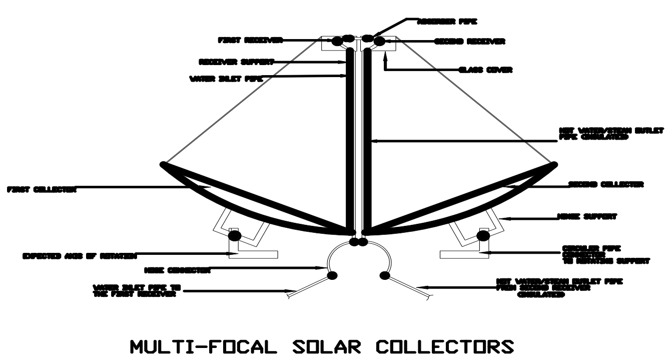

Figure 7. Solar bi-focal collectors assembly.

concentrator aperture diameter edge and the base of the receiver. One of the supports is designed to extend from the concentrator edge to the rotating support.

Taking the larger of the two values arrived at using Euler formula and Rankine formula gives the rod diameter, d = 4.257 mm. For this design, mild steel rod of 8 mm diameter was selected for the support of the receiver since it may be subjected to deflection due to varying collector position and wind actions. Table 1 shows the collectors component parts specification and the assembly of the solar bi-focal collectors is shown in Figure 7.

Conclusion and Recommendations

Solar collectors comprising basic units such as the paraboloid concentrators, receivers and support/connectors have been analysed in this study. The results indicated that two number solar parabolic concentrators each having diameter of the receiver as 0.3 m, aperture diameter of 1.4 m and internal surface area of 1.53 m^2 will be adequate to collect the solar energy required to provide the needed power input of 0.967 kJ/s in the collector's receiver. The analysis will serve as a basis in designing the other component parts such as the tracking and support systems of a solar tracking bi-focal collector system. It is therefore recommended that the procedures used in this work should be applied in the design of solar collectors of parabolic type of other magnitude.

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