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Design and Implementation of a Novel Solar Cooker

Adedipe O. and Abolarin M. S.

Department of Mechanical Engineering, Federal University of Technology, P.M.B 65 Minna, Niger State, Nigeria,

A R T I C L E I N F O

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A B S T R A C T

This work is centered on the design and fabrication of a solar cooker for routine household cooking device. It is a modification of a convectional flat plate collector solar cooker with the use of plane reflectors to increase the energy input to the collector and improving its efficiency. The main features of the cooker box are its rectangular shape, the double-glazing and the adjusting mechanism for the two reflectors at the sides. The solar cooker design is fairly simple and its fabrication was accomplished using inexpensive and locally available materials that satisfy the necessary requirements. The solar cooker comprises of the cooking chamber, reflectors, aluminum foil, aluminum absorber plate, double glazing. The cooker box is made of plywood, silvered glass was selected as the reflector surface, and transparent glass was used for glazing while aluminum sheet was selected as the absorber plate. The solar cooker was tested and the results yielded a maximum of 97^{o}C for the cooker chamber and the efficiency of the solar cooker was 76.74%.

1. Introduction

The most common form of energy utilized throughout the world is solar energy. There are several types of renewable energy sources with which solar still remains as one of the principal renewable energy sources which can be utilized. This energy is derived from the sun. Sun is the source of all sorts of energy and remains as principal deity since human thinking began. The sun our singular source of renewable energy, sits at the centre of the solar system and emits energy as electromagnetic radiation at extremely large and relatively constant rate, which is almost equal to the rate of energy coming from furnace at a temperature of about 5527^{o}C

• Corresponding author.
email address: adelordy2002@yahoo.com

(Charles *et al*, 1979). If we could harvest the energy coming just from 10 hectares of the surface of the sun, we would have enough to supply the current energy demand of the world. (Mayhew, 1972)

However, this cannot be done because of three important reasons. Firstly, the earth is displaced from the sun, and since the sun's energy spreads out like light from a candle, only a small fraction of the sun's energy reaches the earth. Secondly, the earth rotates about its polar axis, so that any collector device located on the earth's surface can receive the sun's energy for only about one-half of each day. Thirdly, there is an atmosphere surrounding the earth's surface. This atmosphere accounts for another 30 percent reduction in the sun's energy. (Folayan, 1988)

For thousands of years now, humans have used solar energy to keep warm and to assist with other activities. Solar cookers of different designs and capabilities have been designed and used in a number of countries like USA, Mexico, Japan, India and Australia, which employ a flat plate collector. Yet they have failed to gain global popularity due to the high initial capital cost, low thermal performance on cloudy or winter days and its design. (Brain, 1992)

This design incorporates side reflectors that are adjustable by placing the box on a rotating stand to track the different positions of the sun's rays and then concentrate them onto the flat plate collector. The primary advantage of these adjustable reflectors is to increase the thermal radiation of the system efficiency and to increase the flexibility. (William, *et al* 1980)

Almost 90% of the energy collected by a solar system occurs between 9 am to 3 pm. The provision for changing the direction of proposed cooker with the horizontal is sufficient to collect direct solar radiation perpendicularly throughout the mentioned period. Thus, radian energy falling per unit aperture area of the cooker face is increased than if the cooker is placed horizontally like conventional box type cooker. Also, transmissivity of the cooker glazing is increased for its perpendicular position with the beam radiation. (Eastop, 1993)

In this cooker system with two reflectors, energy collection is high and even four reflectors can be conveniently used to concentrate solar radiation similar to tracking reflectors, but without the hazards of frequent manual adjustment to follow the apparent motion of the sun. Arrangement of multiple reflectors is also possible in horizontally placed box type cooker, but except of the south facing reflector other reflectors will not be able to reflect radiation properly to the inside of the cooker box except the noon time. This is due to the fact that either effective area of the reflecting surface of the reflectors exposed to the sun will be very less than its actual area or major portion of the reflection from the reflectors will not fall on the cooker inside (Donald *et al*, 1977). The design of solar cooker have evolved along two lines, the distinction being primarily in the manner by which concentration is achieved and the degree to which it is used. The 'focusing or direct type' cooker uses a reflector to concentrate beam radiation onto the food of the cooking vessel in which the food is cooked. This is effectively equivalent to an open fire as a source of cooking energy. The 'box type' cooker is an insulated enclosure with a transparent window on the top exposed to the sun; it works by the green-house effect. Light enters through the window and is absorbed and reflected in the window by the reflectors arranged around it. The sunlight is absorbed and reflected as infra -red radiation (i.e. heat); the transparent window blocks the infra-red, so the heat stays in the box where it cooks food not quite fast but steadily, as there is sufficient heat stored in the cooker to be reached to the food when placed in it. (Eugene, 1997)

2. Materials and Methods

The design analysis contains the theoretical background to the solar cooker box design describes the equation on thermal radiation as they apply to the flat collector and its performance. Thermal radiation consists of electromagnetic waves emitted due to the agitation of the molecules of a body which could be absorbed by the body, reflected from the body and transmitted through the body. (Rajput, 2005)

Design Calculation

Determination of the resistance due to convective heat loss coefficient through the bottom insulation.

The resistance due to convective heat loss is determined by

$$R_1 = \frac{1}{h_c} = \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} \quad (1)$$

Where:
R_1 = The resistance due to convective heat loss (K/W);
k_1,k_2 and k_3 = Thermal conductivities of the inner shell, insulation and outer shell materials (W/mK);
h_c = Convective heat loss coefficient through bottom insulation (W/m^2K).

The resistance due to convective heat loss coefficient through the bottom insulation is determined from Eq. (1) to be 0.676m^{2}K/W

Determination of the resistance due to convective heat loss coefficient between upper glazing and atmosphere.

The resistance due to convective heat loss coefficient between upper glazing and atmosphere is determined by

$$R_6 = \frac{1}{h_{c.ga}} = \frac{1}{5.7+3.8V_w} \quad (2)$$

Where:
R_6 = Resistance due to convective heat loss coefficient between upper glazing and atmosphere (m^{2}K/W);
$h_{c.ga}$ = Convective heat loss coefficient between upper glazing and atmosphere (W/m^{2}K)
The resistance due to convective heat loss coefficient between upper glazing and atmosphere is determined using Eq. (2) to be 0.0598m^{2}K/W

Determination of the resistance due to convective heat loss coefficient between lower glazing and absorber plate

The resistance due to convective heat loss coefficient between lower glazing and absorber plate is determined by

$$R_2 = \frac{1}{h_{c.pg}} = \frac{1}{7.583\left[\frac{T_p - T_c}{T_p + T_c}\right]^{\frac{1}{3}}} \quad (3)$$

Where:
$h_{c.pg}$ = Convective heat loss coefficient between absorber plate and lower glazing (W/m^{2}K);
T_c = Exit air temperature of the collector (K);
T_p = Temperature of the absorber plate (K);
R_2 = Resistance due to convective heat loss between upper and lower glazing (m^{2}K/W)
The resistance due to convective heat loss between upper and lower glazing is determined from Eq. (3) to be 0.2363m^{2}K/W

Determination of the resistance due to radiative heat loss coefficient between glazing and atmosphere

The resistance due to radiative heat loss coefficient between glazing and atmosphere is determined by

$$R_7 = \frac{1}{h_{r.ga}} = \frac{1}{\varepsilon_c \sigma (T_c^2 + T_a^2)(T_c + T_a)} \quad (4)$$

Where:
R_7 = Resistance due to radiative heat loss between glazing and atmosphere (m^{2}K/W)
σ = Stefan-Boltzmann constant (W/m^{2}k^4);
= Glazing emissivity;
T_a = Ambient air temperature (K);
$h_{r.ga}$ = Radiative heat loss coefficient between upper glazing and atmosphere (W/m^{2}K).
The resistance due to radiative heat loss coefficient between glazing and atmosphere is determined from Eq. (4) to be 0.1540m^{2}K/W

Determination of the resistance due to radiative heat loss coefficient between glazing layers

Resistance due to radiative heat loss coefficient between glazing and layers is given by

$$R_5 = \frac{1}{h_{r.gg}} = \frac{\frac{2}{\varepsilon_c} - 1}{4\sigma T_c^3} \quad (5)$$

Where:
R_5 = Resistance due to radiative heat loss coefficient between glazing and layers (m^{2}K/W);
$h_{r.gg}$ = Radiative heat loss coefficient between glazing layers (W/m^{2}K).
Resistance due to radiative heat loss coefficient between glazing and layers is determined using Eq. (5) to be 0.1520m^{2}K/W

Resistance due to radiative heat loss coefficient between lower glazing and absorber plate.

$$R_3 = \frac{1}{h_{r.pg}} = \frac{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1}{\sigma (T_p^2 + T_c^2)(T_p + T_c)} \quad (6)$$

Where:
R_3 = Resistance due to radiative heat loss coefficient between lower glazing and absorber plate (m^{2}K/W);
$h_{r.pg}$ = Radiative heat loss coefficient between absorber plate and lower glazing (W/m^{2}K).
The resistance due to radiative heat loss coefficient between lower glazing and absorber plate is determined from Eq. (6) to be 0.0787m^{2}K/W

Determination of the bottom loss coefficient through insulation due to conduction

The bottom loss coefficient through the insulation due to conduction is given by

$$U_b = \frac{1}{R_1} \quad (7)$$

Where:
U_b = Bottom loss coefficient through the insulation due to conduction (W/m^2K)
The bottom loss coefficient through the insulation due to conduction is determined from Eq. (7) to be $1.479 W/m^2K$

Determination of the top Loss coefficient from the surface due to both radiation and convection

The top loss coefficient from the surface due to both radiation and convection is determined by

$$U_T = \left[\frac{1}{\frac{1}{R_2}+\frac{1}{R_3}} + \frac{1}{\frac{1}{R_4}+\frac{1}{R_5}} + \frac{1}{\frac{1}{R_6}+\frac{1}{R_7}}\right]^{-1} \quad (8)$$

Where:
U_T = Top loss coefficient from the surface due to both radiation and convection ($W/m^2/K$).

The top loss coefficient from the surface due to both radiation and convection is determined using Eq. (8) to be $3.9351 W/m^2K$

Determination of the overall heat transfer coefficient

The overall heat transfer coefficient is determined by

$$U_L = U_t + U_b \quad (9)$$

Where:
U_l = the overall heat transfer coefficient.
The overall heat transfer coefficient is determined from Eq. (9) to be 5.4141

Determination of mass flow rate of air

The mass flow rate of air at 32°C is determined by

$$m_a = \rho_a V_a \quad (10)$$

Where:
m_a = Mass flow rate of air (kg/s);
ρ_a = Density of air (kg/m^3);
V_a = Volume flow rate of air (m^3/s).

The mass flow rate of air was determined by Eq. (10) to be 0.01159Kg/s

Determination of heat gain

The amount of solar radiation entering the oven's interior is given by

$$Q_T = \alpha_p \tau_g A_c I_t \quad (11)$$

Where:
Q_T = Amount of solar radiation entering the cooker's interior (W);
α_p = Absorber plate absorptivity;
τ_g = Glazing transmittivity;
A_c = Cooker bottom area (m^2);
I_t = Intensity of the incident solar radiation on the collector surface (W/m^2K).
The amount of solar radiation entering the oven's interior is determined using Eq. (11) to be 858.85W

Determination of the collector efficiency

The efficiency of the collector is determined by the relation

$$\eta_c = \alpha_p \tau_g - \frac{A_b U_L (T_p - T_a)}{I_t A_c} \quad (12)$$

Where: ηc = Efficiency of the collector;
A_b = Collector area (m^2).
The efficiency of the collector is determined using Eq. (12) to be 27.07%

Determination of the efficiency of the cooker
The efficiency η of the cooker is given by

$$\eta = \frac{Q_u}{Q_T} \times 100\% \quad (13)$$

Where:
η = efficiency of the cooker (%);
Q_u = Useful heat delivered by a solar collector (W).
The efficiency of the cooker is determined using Eq. (13) to be 76.74%

3. Results

After the completion of the solar cooker construction, it was tested during the harmattan season in the month of February. The solar cooker was placed in a horizontal surface, in which the reflectors were manually adjusted to track the radiation of the solar radiation at different times of the day. The temperature-time profile during the test period was recorded using a stop watch and the temperatures were measured using a thermocouple. The ambient temperature, T_a the glazing temperature, T_g and the absorber temperature, T_p were taken with respect to time. Hence, the tests that were carried out were recorded below.

Table 1: Time – temperature profile for Day 1

Time of the day (Hrs)	T_{-a}(°C)	T_g(°C)	T_p(°C)
9.00am	29	27	44
10:00am	31	64	72
11:00am	34	68	78
12:00 noon	34	76	96
1:00pm	34	71	94
2:00pm	33	71	88
3:00pm	33	66	82

Table 2: Time-temperature profile for Day 2

Time of the day (Hrs)	T_{-a}(°C)	T_g(°C)	T_p(°C)
9.00am	29	33	48
10:00am	32	65	73
11:00am	32	73	88
12:00 noon	33	78	97
1:00pm	35	75	96
2:00pm	34	70	86
3:00pm	34	68	88

Table 3: Time-temperature profile for Day 3

Time of the day (Hrs)	T_{-a}(°C)	T_g(°C)	T_p(°C)
9.00am	30	35	51
10:00am	32	64	70
11:00am	32	68	83
12:00 noon	34	73	97
1:00pm	33	71	88
2:00pm	32	71	87
3:00pm	32	67	82

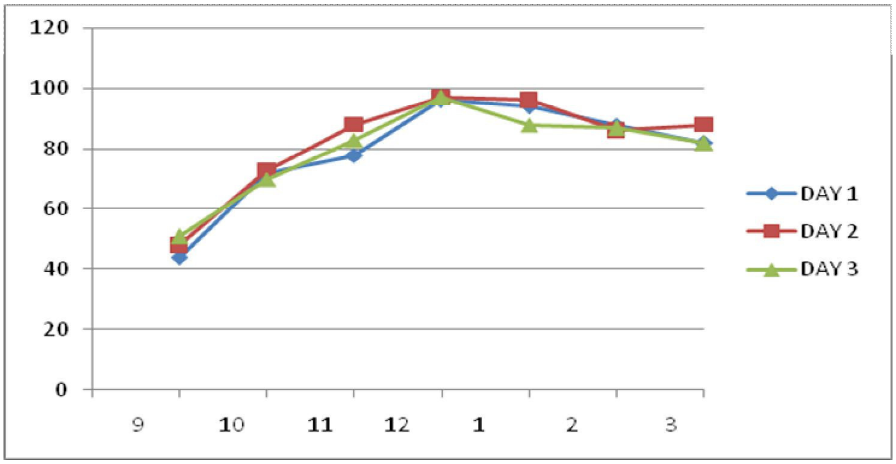

Fig. 1: Variation of cooker chamber temperature with time

4. Discussion

On the first day of the experiment, no cooking was done. The atmosphere was a little bit dense and dusty because of the harmattan. The time and the temperature readings are shown in table 1 above. On the second day of the experiment, a pot of water was placed inside the cooker chamber; the oven box was kept in the sun for a while so that the cooker chamber could be heated until the water temperature was reading 93^{o}C. The temperature was constant for awhile due to the fact that the water was absorbing the heat. The ambient temperature during this period was 32^{o}C. The temperature readings were also recorded as shown in the table 2. On the third day no cooking was done, and the weather was dusty and dense as compared with the other two days. It could be observed from the tables that the cooker attained much higher temperatures between 12noon and 3:00pm, which implies that cooking, could be done at this time of the day. The variation of the cooker's chamber temperature (absorber plate temperature), T_p with the time of the day were shown in figure 1above. The variation of the temperature with the time profile curve followed identical pattern of rising towards mid day and gently dropping as the sun sets.

5. Conclusions

The solar box design so far could be seen to increase the energy yield of convectional Flat plate redirect sun rays falling at the sides of the collector unto the absorber plate. The reflector are hinged and guided in the required position by reflection adjusting mechanism. In designing the system factors such as cost, availability, and some useful properties of the materials were taken into consideration. The solar cooker box was easy to construct and also easy to use as the reflectors have an adjusting mechanism which is very simple to set and concentrate the sun rays. Under test room the system exhibited performance characteristics which are typical of most solar base devises; its infectiveness is dependent on variation in solar radiation intensity of the location. Since the unit is inexpensive, easy to make, operate and maintain, it is propose here that this unit should be considered for adoption and use as complementary device for household cooking, so that the rate of consumption of non-renewable energy and the total dependency on other convectional energy sources would be reduced.

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