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Exergy Analysis of a Multiple Reflector Solar Box Cooker

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Abstract

This paper presents the exergy analysis of a typical multiple reflector solar box cooker. The fabricated cooker having multiple reflectors experimented in the summer day period at the premises of the University of Ilorin, Ilorin, Nigeria. Thermodynamics analysis was conducted to obtain performance evaluation of the cooker through applications of energy and exergy equations at ambient temperature. The results obtained show an increase in the exergy efficiency of the cookers concerning an increase in the number of reflectors used in construction.

Keywords: Cooker, energy, exergy, reflector

I. INTRODUCTION

Solar cooker is a heating device that has reduced the overdependence on fossil fuel energy especially in the areas where tapping of solar energy is easily achievable in recent times. This device has been produced in different configurations in the past to meet a particular need.

As a viable source of renewable energy, it is known that solar energy is a typical source of energy that makes solar cooker operational. This source of energy has found applications since time immemorial to perform the drying of agricultural products, provide space heat in cold seasons, ease ventilation in homes and power various appliances as used in many developed and developing countries [1].

Owing to the availability of solar system especially in the equatorial region, the solar system thus generates alternative cooking fuel for several households all over the world and thereby creates fossil fuel reserves. The increasing dearth of firewood as a result of chronic deforestation has also necessitated the application of the solar system as an alternative for cooking fuel [2].

This has therefore provided a viable solution to the problem of deforestation and depletion of the ozone layer in that region of the world when utilized adequately.

Researchers have previously worked on the subject of evaluating the thermal behaviour of the solar cooker which has a reflector and also without the use of reflector. A plywood body cooker with plane reflector and made a stream relief hose in the cooking pot which went through the sidewall to remove steam from the cooking chamber into the atmosphere was built by a group of researchers [3]. In this experiment, the values of the temperature and boiling time as recorded without reflector being used with the cooker were 119º C and 70 min and with reflector in used was 138º C and 60 min.

Similarly, [3] gave an account of another experiment performed on a solar cooker with and without reflector. In this research work, a box solar cooker with reflector was fabricated and its thermal performance was evaluated to compute its efficiency. Temperature profiles without load and with load as obtained for the cooker gave clarity about its good thermal performance and the capacity to boil water. The efficiency of the cooker without reflector was estimated to be 96% while with reflector, it was approximately 99%.

It was further observed that as a result of rising temperature differences between plates and ambient temperature, the efficiency of cooker increases while it decreases with a reduction in solar radiation. This result confirms its reliability for baking and boiling water.

However, this research work places emphasis on exergy analysis of a rectangular solar box-cooker using foil reflectors with a reflective capacity that are capable of utilizing the energy released from the shining sun to cook in Ilorin, Kwara State, Nigeria with the geographical coordinate of latitude 8.4910º N and longitude 4.5952º E Ilorin (University of Ilorin precisely) for an average observable sunshine of 9.0 hours per day.

The thermodynamic assessment of the solar cookers is carried out through an evaluation of its energy and exergy efficiencies. In determining the energy efficiency of a solar cooker, the ratio of the energy received by the solar cooker to the input energy is usually considered to obtain results. Exergy efficiency is believed to account for the temperatures related to energy transfers to and from the solar cooker, as well as the quantities of energy transferred and it consequently provides a measure of how nearly solar cooker approach ideal efficiency [4].

II. MATERIALS AND METHODS

II.1 DESCRIPTION OF THE SYSTEM

The pictorial representation of the solar cooker analyzed in this work is shown in Figure 1. The materials used in the design and construction of the cooker include; Teak (*Tectonagrandis)*, Aluminum foil, Aluminum sheet, fibre glass wool, glass, plywood and reflectors, which were all sourced for at local market in Ilorin Kwara State Nigeria [1].

The cooker was positioned in the sun after construction to collect solar energy. A type-K thermocouple (MTM- 380SD model) was used in reading the temperature inside the cooker.

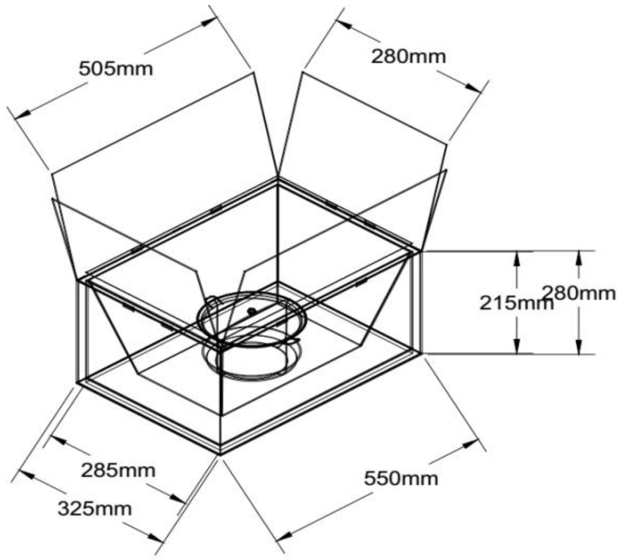

Figure 1: Isometric view of solar box cooker

The design dimension of the cooker whose schematics is shown in Figure 1 is as follows;

Length of outer box = 550 mm

Breath of outer box = 325 mm

Height of outer box = 280 mm

Length of inner box = 505 mm

Breath of inner box = 285 mm

Height of inner box = 215 mm

Black plate Absorber length = 380 mm

Black plate Absorber breath = 230 mm

Length of glazing mirror = 510 mm

Breath of glazing mirror = 290 mm

Length of small side reflector (Side 1 & 3) = 325 mm

Breath of small side reflector (Side 1 & 3) = 300 mm

Length of large side reflector (Side 2 & 4) = 500 mm

Breath of large side reflector (Side 2 & 4) = 300 mm

Glass thickness = 4 mm

Refractive Index of mirror = 1.5

Aluminum foil reflectance = 0.95

Diameter of black pot = 15 cm

Height of black pot = 12 cm

Using the above dimension, the area of the outer box of the cooker is determined using Equation (2.1).

Area of outer Box (cuboid) = 2LB + 2LH + 2BH (2.1)

= 2(550)(325) + 2(550)(280) + 2(325)(280)

357500+308000+182000

= 847500 mm^2

= 0.8475 m^2

The area of the outer box is determined from Equation (2.2) as described below.

Area of inner Box (cuboid) = 2LB + 2LH + 2BH (2.2)

= 2(505) (285) + 2(505)(215) + 2(285)(215)

293550+267800+148200

=709600 mm^2

= 0.7096 m^2

However, Equation (2.3) was used to calculate the areas of the reflectors.

Area of side 1 and 3 Reflectors = L x B (2.3)

= 500 x 300

= 150000 mm^2

= 0.15 m^2

Area of side 2 and 4 Reflectors = L x B

= 325 x 300

= 97500 mm^2

= 0.0975 m^2

Equation (2.4) was used to calculate the volume of the cooker aperture.

Volume of cooker Aperture = L x B x H (2.4)

= 505 x 215 x 285

= 30943875 mm^3

= 0.3094 m^3

Equation (2.5) was used to calculate the volume of pot on the plate absorber.

Volume of Pot = $\pi r^2 h$ (2.5)

= 3.142 x 7.5^2 x 12

= 2120.85 mm^3

= 0.0000212085 m^3

Space volume around the pot in the cooker

= 0.3094 – 0.0000212085

= 0.30937879 m^3

II.2 ENERGY ANALYSIS

In performing energy analysis of the solar cooker, it is important to consider the amount of input and output of energy for evaluation. Given that the kinetic and potential energy terms are considered negligible and for the steady-state flow process during a finite time interval, the expression of energy balance of the solar cooker as follows [4]:

Energy Input = Energy Output +Energy Loss

Where energy input to the solar cooker represents the total solar energy that is incident upon the plane of the solar cooker per unit time per unit area [5].

Thus, the mathematical equation of the energy input which symbolizes the total input incident energy according to [6] is expressed as follows;

$$Q_{incident} = I_{av} \cdot A_{sc} \quad (2.6)$$

where; $Q_{incident}$ is the solar cooker energy input in W; I_{av} is the average solar intensity during the interval Δt (W/m^2), and A_{sc} is the area of the cooker aperture in m^2.

Energy output that represents the proportion of energy used by the solar cooker is determined from the expression of Equation (2.7) as follows;

$$E_o = m_w C_w \Delta T \quad \text{where;} \quad (2.7)$$

m_w = Mass of water (kg)

C_w = specific heat capacity of water (J/kg/K)

ΔT = difference between maximum temperature of water and ambient temperature(℃).

From the expression of first law of thermodynamics, energy efficiency is defined as;

$$\eta = \frac{Energyoutput(E_o)}{Energyinput(E_i)}$$

$$\eta = \frac{m_w C_w \Delta T}{I_{av} A_{sc} \Delta t} \quad (2.8)$$

II.3 EXERGY ANALYSIS

Exergy is regarded as a measure of the quality or grade of energy which can be destroyed in a thermal system [7]. In the context of solar cooker, [5] defined exergy efficiency as the ratio of the exergy gained by the solar cooker (exergy output) to the exergy of the solar radiation (exergy input).

The expression of the exergy efficiency as given by [8] is presented in Equation 2.9 and 2.10 as follows;

$$\psi = \frac{Exergyoutput}{Exergyinput} \quad (2.9)$$

$$= \frac{m_w C_{pw}\left[\left(T_{wf} - T_{wi}\right) - T_a In\left(\frac{T_{wf}}{T_{wi}}\right)\right] \Big/ \Delta t}{I_{av}\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] A_c} \quad (2.10)$$

Where;

m_w denotes the mass of water in the cooker in kg

C_{pw} represents the specific heat capacity of water in J/kg ^0C

T_{wf} is the final temperature of water in ℃

T_{wi} represents the initial temperature of water in ^0C

T_a is the ambient temperature in ^0C

Δt is time difference in seconds (s)

I_{av} is the solar radiation in W/m^2

T_s is the sun temperature (5,800 K) and;

A_c is the area of the aperture of the solar cooker in m^2

III. RESULTS AND DISCUSSION

III.1 EXPERIMENTAL DATA FOR THE ANALYSIS

The data obtained from the experiment of the solar cooker by [1] was used to perform the exergy analysis of the cooker. Using this data and given that;

Mass of water (m) = 1 kg

Specific heat capacity of water (c) = 4,200 J/kgK

Average solar intensity during the interval Δt (I_{av}) = 953.5 W/m^2

Area of aperture of the cooker (A_c) = 0.06410 m^2

The ambient temperature (T_a) = 33.3℃

Then the other variables required for estimating the values of energy and exergy efficiencies of the cooker are presented in Table 3.1 below.

Table 3.1: Experimental data of the multiple reflector solar cooker

S/N	Class of solar cooker (AR) m^2	HTW ^0C	Δt (min)	T_{wf} ^0C	ΔT ^0C
1	NR	50.4	185	50.4	15.3
2	1R (0.15)	66.1	160	66.1	31.0
3	2R (0.2475)	75.6	145	75.6	40.5
4	3R (0.3975)	85.3	122	85.3	50.2
5	4R (0.495)	100	110	100	64.9

*HTW is the highest temperature reached of water during sensible heat test, *ΔT is the difference in temperature

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between the highest temperature of water recorded and the ambient temperature, *Δt which is the time taken to achieve the maximum water temperature, *AR is area of reflector, *NR is Cooker with no reflector, *1R is cooker with one reflector, *2R is cooker with two reflectors, *3R is cooker with three reflectors and *4R is cooker with four reflectors.

III.2 ENERGY EFFICIENCY OF THE SOLAR COOKER

The energy efficiency of the solar cooker is determined from Equation (2.8).

The energy efficiency analysis evaluates the thermal performance of the solar cooker at the highest temperature of water during sensible heat test. This highest temperature is taken to be the final temperature of water for each class of solar cooker.

The results of energy efficiency as obtained for each class of the solar cooker is presented in Figure 3.1

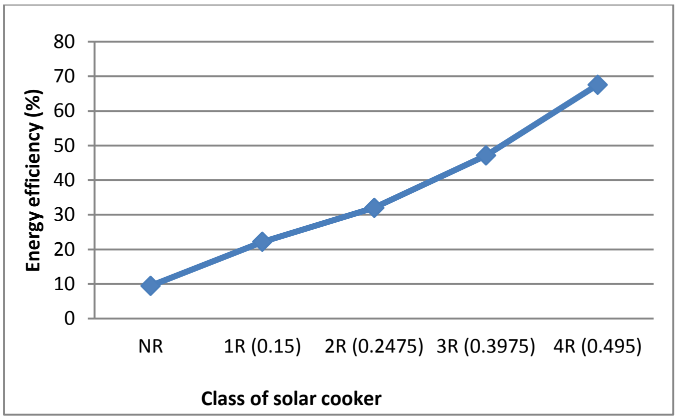

Figure 3.1: Result of energy efficiency for each class of solar cooker

From Figure 3.1, it is evident that the value of energy efficiency increases with an increase in the number of reflectors used for the solar cooker considered in the experiment. This result as obtained validates the first law of thermodynamics which confirms that the total input energy into the system equals the total output energy. The reflector as used in the experiment functioned to aid the intensity of solar thermal energy and was a crucial factor that determines the rate of increase in the final temperature of the water available in the solar cooker.

III.3 EXERGY EFFICIENCY OF THE SOLAR COOKER

Irreversibility is a regular phenomenon that is associated with the heat transfer process. The exergy analysis is performed to ascertain the ideal efficiency of the system using the results obtained from the computation of exergy output and input. This analysis is carried out with reference to the ambient temperature condition which was found to be $33.3^0 C$ during the period of the conduct of the experiment.

Exergy efficiency obtained for each class of cooker is shown in Figure 3.2 below.

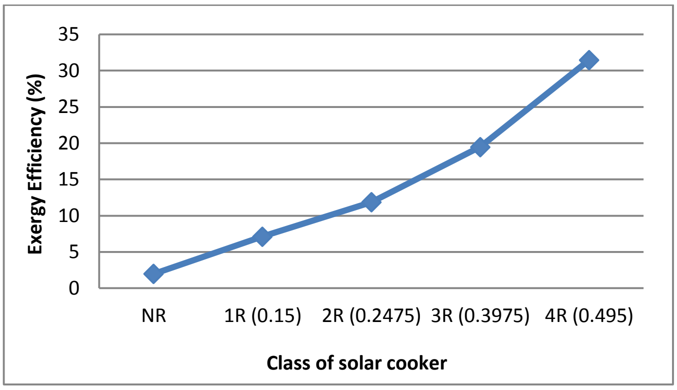

Figure 3.2: Result of exergy efficiency for each class of solar cooker

Exergy analysis which is known to be based principally on the second law of thermodynamics, as compared to energy analysis, which operates based on the principle of thermodynamics first law, takes into account and elaborate on the quality of the energy transferred [9].

The result obtained in Figure 3.2 indicates that an increase in the number of the reflectors used in the experiment enhances the efficiency of the solar cooker.

Moreover, [4] also reported in their work that when reflectors are added, there is the corresponding improvement in efficiency and thermal performance of the solar cooker. In general, whenever exergy efficiency is compared with the energy efficiency of the box solar cooker, the value of energy efficiency is considerably higher than the exergy efficiency. This reason as underlined by [10] explains that to compute the energy efficiency, only the quantity of the energy transferred is taken into consideration while the quality of the energy transferred is ignored.

IV. CONCLUSION

The outcome of the experimentation of the multiple reflector solar cookers as conducted in this work shows that the overall thermal efficiency of the solar cooker improves significantly with an increase in the number of the reflector used. This is evident from the results obtained in the analysis whereby the highest exergy efficiency of 31.47 % was obtained with a solar cooker having four reflectors as compared with a cooker without reflector which has an exergy efficiency of 2 %.

However, exergy analysis as conducted presents a more realistic approach for obtaining performance evaluation of the solar cooker and a model for such evaluation especially in the location of conduct of the experiment.

The exergy result obtained would guide in the selection of each class of the cooker for various thermal applications and also provides valuable information about the effect of the magnitude of irreversibility that occurs in the system.

Finally, future work is recommended in the area of reducing irreversibility that occurs in the system to obtain an improved exergy efficiency of the solar cooker.

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