



Experimental Studies of Solar Box Cooker Using Energy and Exergy Efficiency Analysis in a Semi-Arid Environment

H. Musa, M. B. Maina, A. T. Abdulrahim
Department of Mechanical Engineering,
University of Maiduguri Borno State Nigeria.

ABSTRACT

This work presents evaluation of the energy end exergy efficiency of box-type solar cooker (SC) in Maiduguri (North-eastern Nigeria). Energy and exergy analysis was applied to solar cooker (SC). Thermodynamic considerations required to developed rational and meaningful methodologies for the evaluation of the efficiency of the SC was studied. It was found that the average daily water temperature from 10:00 to 12:00 solar time was 83.5 °C in the SC. The average daily temperature difference in the SC was 42.4 °C. The energy output of the SC varied between 1.38W and 49.58 W for the SC for the same time interval with an average energy output of 25.9 W SC. The exergy output for the SC ranged from 0.81W to 18.67 W for the SCK for the same time interval with an average exergy output of 8.67W for SC. A linear and polynomial regression of the plotted points was used to find the relationships between energy/exergy outputs, and efficiencies and temperature difference. The energy and exergy outputs at a temperature difference of 50 °C for the SC was estimated to be 14.48 W and 9.95 W. The energy efficiency for the SC was in the range 0.29% –10.75% and exergy efficiency in the range of 0.18% –5.21% during the experimental period.

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INTRODUCTION

The energy sector is widely acknowledged to be indispensable for the smooth sailing of any economy; it is a vital element in human life and a pivotal input for social and economic development (Ebenezer *et al.*, 2015). The situation in the rural areas of the country is that most end users depend on fuel wood. Fuel wood is used by over 70% of Nigerians living in the rural areas (Sunday, 2012). Nigeria consumes over 50 million tonnes of fuel wood annually, a rate which exceeds the replenishment rate through various afforestation programs. Sourcing fuel-wood for domestic and commercial uses is a major cause of desertification in the arid-zone states and erosion in the southern part of the country. The absence of reliable energy supply has not only left

the rural populace socially backward, but has also left their economic potentials untapped. Fortunately, Nigeria is blessed with abundant renewable energy resources such as solar, wind, biomass and small hydropower potentials. The logical solution is increased penetration of the renewable energy supply that is safer and environmental friendly resource which is also helpful for solving energy crisis and environmental problems, (Sunday, 2012). The concept of solar cooking started at the beginning of second century. All solar cookers work on the principle of collecting the direct solar rays to raise temperature of food or water. A solar oven or solar cooker is a device which uses sunlight as its energy source. Because they use no fuel and they cost nothing to run, solar cookers fall into



two categories – solar ovens and direct solar concentrators. The basic design for a solar oven is that of a box with a glass cover. The box is lined with insulator and a reflective surface is applied to concentrate the heat onto the pots. The other approach is to reflect the sun's onto a pot, often with a parabolic dish, (Pawar and Aradhya, 2012).

Maiduguri shares local boundaries with Konduga, Jere and Mafa LGAs. It has an area land mark of 300 square kilometres (300 km²), which lies between latitude 12° N to 13° N and longitude 13° E to 15° E respectively. The vegetation is of semi – arid zone and climatic condition in this area is of a hot dry season (27°C to 42°C), and an annual rainfall of 500 mm to 600 mm has been recorded (Mohammed *et al.*, 2017).

Solar cookers have been subjected to several types of tests to rate its performance. Mullick *et al.*, (1987) presented a set of tests procedures and

equations to assess the thermal performance of the solar cookers especially the box type cookers. Their recommendations later got adopted by Bureau of Indian Standards (BIS), and there results were expressed as factor of merit. In the recent past, Patela (2005), concentrated on exergy aspects, however, it was in the year 2000 that Funk found a need to evolve an International Standard for testing solar cookers. The recommendations were later adopted by American Society of Agricultural Engineers (ASAE S580). Therefore this paper intends to: evaluate the energy end exergy efficiency of box-type solar cooker under Maiduguri climatic condition as well as use linear and polynomial regression of the results to find the relationship between the temperature difference and the energy and exergy output in terms of intercept A(w) and slope B (W/C) or $y=A +BT_d$

Table 1: A summary of the studies on the energy and exergy of the solar cooking technology

Author (published date)	Brief Title	Cooker type	Focused feature	Highlight
Ozturk (2004)	Energy and Exergy Efficiency of parabolic SC	Indirect concentrating cooker	Performance	Evaluating the Energy and Exergy Efficiencies of a parabolic SC
Ozturk (2004)	Energy and Exergy Efficiency of Box-Type SC	Box cooker	Performance	Evaluating the Energy and Exergy Efficiencies of a Box-Type SC
Ozturk (2007)	Comparison of Energy and Exergy Efficiency of Box-Type and parabolic SC	Concentrating and Box Cooker	Performance	Evaluating the Energy and Exergy Efficiencies of a Box-Type and parabolic SC
Kaushik (2008)	Energy and Exergy Efficiency of paraboloidal SC	Indirect concentrating cooker	Performance	Presenting and Evaluation of a domestic-size and commercial-size cooker

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Author (published date)	Brief Title	Cooker type Indirect concentrating cooker	Focused feature	Highlight
Mawire et al (2008)	Energy and Exergy Analyses of a charging storage system	Indirect concentrating cooker with thermal storage	Performance	Presenting a high efficiency cooker with a packed oil pebble bed as the thermal storage
Panwar et al (2012)	State of the Art of Cooking : Overview	Box-Type and Concentrating cooker	Performance	Reviewing performance test and Economic evaluation of SC
Pandey (2012)	Comparative Experimental study of solar cookers using Exergy Analysis	Box-Type and concentrating cooker	Performance	Investigating the effect of water load on the Energy and Exergy efficiencies of SC
Saravanan and Janarthanan (2014)	Energy and Exergy Analysis of double exposure Box-Type SC	Box-Type cooker	Performance	Investigating the effect of cooking vessel on energy and Exergy efficiencies of Box-Type cooker
Farooqui 2015	Impact of load on the Energy and Exergy of SC	Indirect concentrating cooker	Performance	Investigating the effect of Ambient temperature and water load on the Energy and Exergy efficiencies of a Vacuum tube based cooker
Ademola (2015)	Energetic and Exergetic Evaluation of Box-Type SC using different insulating material	Box-Type	Performance	Investigating the effect of the type of insulating material on the Energy and Exergy efficiencies of Box-Type SC
Terres (2015)	First and second Law efficiencies in the cooking process of	Box cooker	Performance	Determination of first and second Law efficiencies for Box-Type SC



Author (published date)	Brief Title	Cooker type	Focused feature	Highlight
	eggplant using Box-Type SC			
Iqra et al (2018)	Energy and Exergy-based thermal Analysis of a Bakery unit	concentrating	Performance	Investigating the procedure of thermal analysis of a solar concentrating technology-based bakery unit

METHODOLOGY

Principles of Solar Box Cooker Design

The design parameters considered includes the energy requirements for cooking and daily average insolation. The energy requirement for cooking per person as explained in Mullick, (1987) is about 900 kJ of fuel equivalent per meal. The design of the solar box cooker constructed for this solar energy study has been based on the work of Farooqui, (2015). A solar box cooker as discussed in Funk, (2000). Should be sized in consideration of the largest amount of food commonly cooked, if the box needs to be moved often, it should not be so large so that this task is not too difficult and the box design must accommodate the cookware that is available or commonly used. In order for the box to get higher interior temperatures, the walls and the bottom of the box must have good insulation (heat retention) value. There are hundreds of different designs of solar box cookers in use. These vary in size, material, insulation and components used (Mawire *et al.*, 2008).

Description of the Realized Solar Cooker

The specific dimensions of the outer and inner box were approximately

720 × 720 × 360mm. The hot box dimensions are 500 × 400 × 445 × 125 mm. The space between the outer tray and outer box was filled of glass wool. The inner tray and outer boxes were painted dull black to absorb maximum solar energy. The leakage from the box to the surroundings was minimized by having a rubber gasket (1.5 mm thick) in between the triple glass cover (25 mm glazing) and the box. The absorber trays of both cookers were painted black on both sides. The cooking vessel used in this study was bought from the local market, it is made of Al alloy (18 cm in diameter and 10 cm in height) in a cylindrical dish shape and painted black which allows for high absorption of solar radiation designed to kept cooking, filled with water and equipped with a black cover, was placed into the solar box cooker.

Construction of the Box-Type Solar Cooker

The constructed box-type solar cooker consisted of four components, namely; box made of wood as container, absorber plate (heat collector), glass cover and heat insulator as shown in Figure 1

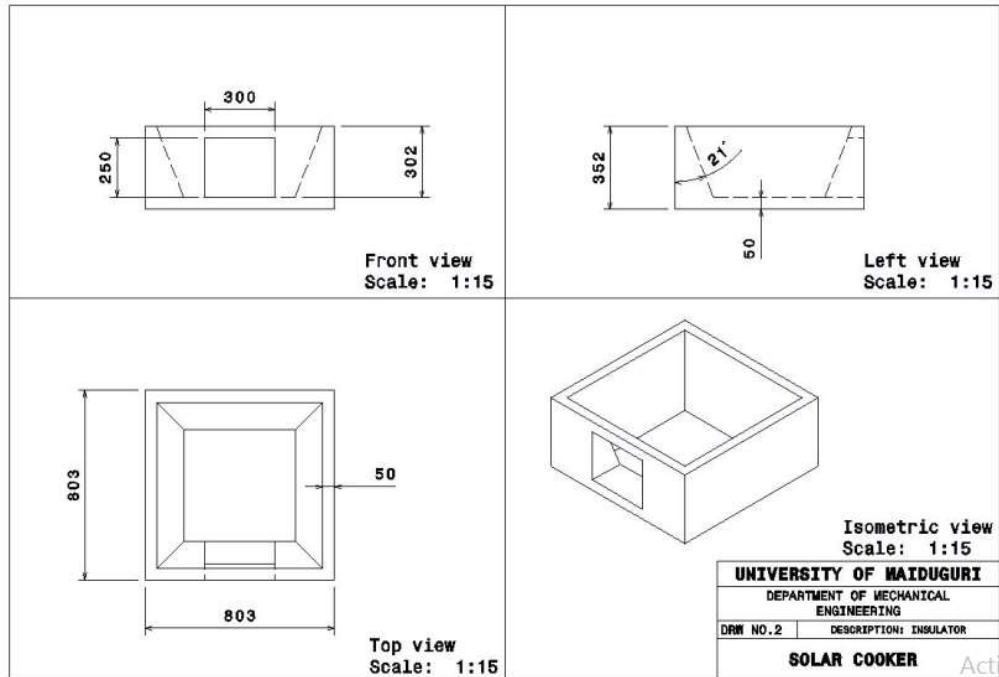


Figure 1. Isometric view and details of box-type solar cooker.

Energy Analysis

Energy input is given by

$$E_i = I_s * A_{sc} \dots \dots \dots 1$$

Where I_s is the solar radiation and A_{sc} is area of aperture of solar cookers

Energy output is given by

$$E_o = M_w C_w (T_{wf} - T_{wi}) / \Delta t \dots \dots \dots 2.$$

Where M_w is mass of water, C_w is specific heat of water, T_{wf} is final temperature of

Water, T_{wi} is initial temperature of water, Δt is time difference.

An energy efficiency of the solar cooker can be defined as the ratio of the energy gained by the solar cooker

(Energy output) to the energy of the solar radiation (energy input).

$$\eta = \frac{\text{Energy output}}{\text{energy input}} = \frac{E_o}{E_i} \dots \dots \dots 3$$

Exergy Analysis

For the steady-state flow process during a finite time interval, the overall

exergy balance of the solar cooker can be written as follows:

$$(\text{Exergy})_{in} = (\text{Exergy})_{out} + (\text{Exergy})_{loss} + \text{Irreversibility}$$

The availability of the terrestrial solar radiation obtained by superposition of the availabilities of two lumped sources, a direct beam source and diffuse

source. The availability (exergy) of a solar flux with both beam and diffuse components can be represented by

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$$\epsilon_i = I_b \left[1 - \frac{4T_a}{3T_s} \right] + I_d \left[1 - \frac{4T_a}{3T_s^*} \right] \dots \dots \dots 4$$

Where: ϵ is the exergy of solar radiation (W/m^2); I_d is the intensity of beam radiation (W/m^2); I_b is the intensity of direct radiation (W/m^2); T is the ambient temperature

(K); T_s is the sun temperature (K); and T_s^* is the effective diffuse radiation temperature (K).

The Patela expression for the available energy flux, which has the widest acceptability, can be used to calculate the exergy of solar radiation as the exergy input to the solar cooker, i.e

$$\epsilon_i = \left[1 + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) \right] A_{sc} \dots \dots \dots 5$$

Where; T_a is the ambient temperature (K). The sun's black body temperature of 5762 K results in a solar spectrum concentrated primarily in the 0.3-3.0 μm wavelength band (Terras *et al.*, 2015). Although the surface

temperature of the sun (T_s) can be varied on the earth's surface due to the spectral distribution, the value of 5800 K has been considered for T_s . The thermal exergy at temperature T is given as:

$$\epsilon_i = \int_{T_0}^T M C_p \left(1 - \frac{T_0}{T} \right) dQ \dots \dots \dots 6$$

Equation (6) can be applied for non-isothermal processes. Thus, the thermal exergy content of water ϵ at temperature T_i can be calculated by the following equation:

$$\epsilon(T_i) = M_w C_{pw} \left[(T_{wi} - T_0) - T_0 \ln \frac{T_{wi}}{T_0} \right] \dots \dots \dots 7$$

When the temperature of water is increased to temperature T_f , the exergy is defined as:

$$\epsilon_o = \frac{M_w C_{pw} \left[(T_{wf} - T_{wi}) - T_a \ln \frac{T_{wf}}{T_{wi}} \right]}{\Delta_t} \dots \dots \dots 8$$

The exergy efficiency is formed as the ratio of the exergy transfer rate associated with the output to the exergy transfer rate associated with the necessary input. An exergy efficiency of

the solar cooker can be defined as the ratio of the exergy gained by the solar cooker (exergy output) to the exergy of the solar radiation (exergy input).

$$\psi = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\epsilon_o}{\epsilon_i} = \frac{M_w C_{pw} \left[(T_{wf} - T_{wi}) - T_a \ln \frac{T_{wf}}{T_{wi}} \right] / \Delta_t}{I_s \left[1 - \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 - \frac{4}{3} \frac{T_a}{T_s} \right] A_{sc}} \dots \dots \dots 9$$

Experimental Apparatus and Procedure

The experiments were conducted at centre for entrepreneurship and enterprises development (CEED) university of Maiduguri. The latitude, longitude and altitude of University

campus in Maiduguri are, respectively, 11°51' N, 13°08' E and 354m above sea level. The experiments were conducted April 2019. During all experiments, the radiation intensity on a horizontal surface was measured using a digital pyrometer

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(SPM-1116SD) (accuracy 0.1W/m^2), (MTM-3801) digital thermometer with three (3) channel contact thermocouples (accuracy 0.1°C) was used to measure the temperature at different locations of the cookers; namely; the cooking fluid, the absorber plate and the ambient temperature was measured. In addition, measuring cylinder was used to measure the volume/mass of water. Ambient temperature, absorber plate temperature, initial water temperature, maximum water temperature and boiling water temperature were measured and recorded at 15 min intervals. The recorded data was used for thermal energy and exergy efficiency of the constructed solar cookers wind speed was

measured by anemometer (ABH-4224) (accuracy 0.1m/s). The international test standard requirements for temperature range and insolation were applied for the SBC on each day. The efficiency of the SBC was evaluated with the water heating tests.

RESULT AND DISCUSSIONS

The cooker was set for test from 9:30 to 16:00. The foregoing is interpretation of the result recorded. Studies on solar box cooker has been carried out based on energy and exergy analysis Figure 1 shows the variation in the environmental conditions during the three hours' water heating test.

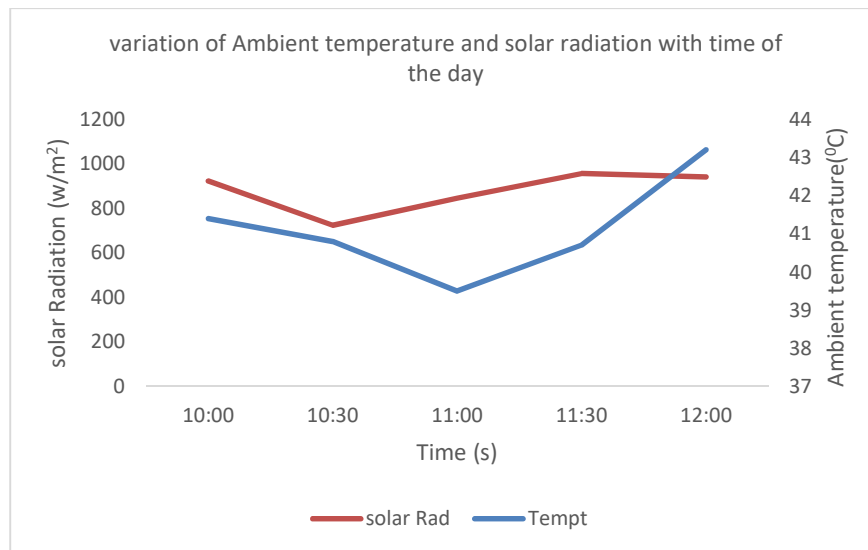


Figure 2: variations of ambient temperature and solar radiation with time of the day

The change of the water temperature in the pot for the SC is shown as a function of time as indicated by Fig. 2, the water temperature in the pot for the SC increased as the outside solar radiation increased during the experimental period. Initially the water temperature difference in SC was small; it increased with time. The water temperature in the SC varied between 30.5°C and 98.5°C as indicated in (Fig. 2). The ambient temperature varied between

39.5°C to 43.2°C , whereas the solar radiation ranged from 723.5 W/m^2 to 956.6 W/m^2 during the experimental period. It was calculated that the average daily water temperature from 10:00 to 12:00 solar time was 85.02°C in the SC. Most important is that the maximum water temperatures of the SC was 98.5°C ; after 3 hrs from the start of the experiment. The result is similar to the result reported by Iqra *et al*, (2012).

When the average daily and maximum temperature of water in the SC was taken into account, the temperature difference of water was 36.8°C. This good performance was due to the thermal

conductivity properties of the insulator of the SC. In the present experiment the heating effect of the SC was similar in comparison with the results obtained by Kaushik and Gupta, (2008).

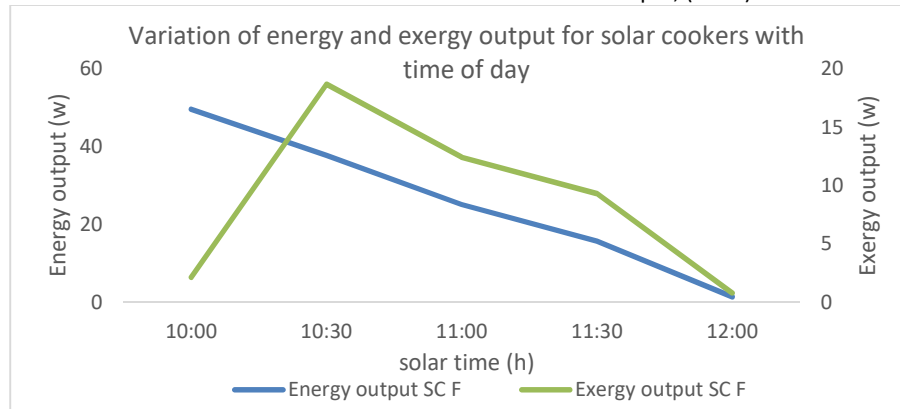


Figure 3: Variation of energy and exergy output for solar cooker with time of day

The energy output of the SC (heating power) was corrected to a standard solar radiation of 700 W/m² by multiplying the observed energy output by 700 W/m² and dividing by the average solar radiation recorded during the corresponding interval. Adjusted energy output and temperature difference were calculated every 30 min for the SC. Fig. 3 shows the variation of the adjusted energy and exergy output as a function of time for the SC. The energy output of the SC ranged between 1.38W and 49.8W for the SC for the period of time covered as

shown by Fig. 3. The energy output for each SC increased at a fast rate in the first one hour, and then decreased during 11:00–12:00. The energy output of the SC dropped from 40.18 W (at 10:30 in the morning) to 0.87W at 12:00 in the early afternoon. The average daily energy output for the SC was 23.81W. This finding affirms the assertions of Kaushik and Gupta, (2008) that solar box cookers power ranges from 20W to 100 W. The energy output for the SC depends strongly on the water temperature.

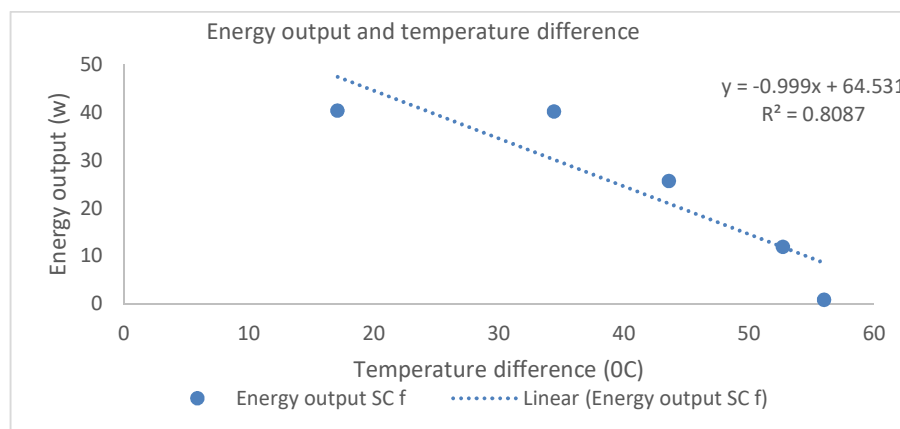


Figure 4: Energy output and temperature difference



The exergy output for the SC was significantly different from the energy output during the water heating tests. For the period of time covered by Fig. 4, the exergy output for the SC ranged from 0.81W to 18.67 W. It was found that the average daily exergy output for the SC was 8.66 W. The study showed that the energy output SC was always greater than the exergy output. For the same time interval, the energy output was about 66.7% more than their exergy output. This difference is due to the fact that the quality of the energy was taken into account to calculate the exergy output calculated from Eq. (8). However, in the calculation of the energy output Eq. (2), the quantity of the energy was taken into account. Fig. 4 represents the relationships between the energy and exergy outputs of the SC, and the temperature difference. A linear and polynomial regression of the plotted points was used to find the relationship between energy output and temperature difference in terms of intercept (W) and slope (W/°C). As indicated by Fig.4, the energy output decreased as the temperature difference increased for the SC, it can also be seen that the energy output of the SC changed linearly with the temperature difference. The slope of the energy output regression line correlates to the heat losses independent of the solar intercept area. Energy output depending on the temperature difference for SC tested is given by equation (11) with a linear regression coefficient $R^2 = 81\%$. The value of energy output is calculated for a temperature difference of 50 °C using relationships determined as 14.6W. It is reported [4] that the coefficient of determination (R^2) or proportion of variation in energy output that can be attributed to the relationship found by regression should be better than 75%. The value for standardized energy output (W) was computed for a

temperature difference of 50°C using the above-determined relationships for the SC. The energy output at a temperature difference of 50°C was estimated to be 14.6W for the SC. Ozturk, (2007) also obtained the relationship between energy output and temperature difference $E_o = 109.96 - 1.67\Delta T$. It can be seen that the derived relationship for the SC obtained in the present research (Eq 11) $y = 64.531 - 0.999\Delta T$ is similar to the relationship of Ozturk, (2007). From Fig. 4, it can also be seen that the exergy output of the SC change linearly with the temperature difference.

A polynomial regression of the plotted points was used to find the relationship between exergy output and temperature difference. By equation (4) for SC with a polynomial regression coefficient $R^2=92\%$. The exergy output of the SC increased gradually with the temperature difference, and then decreased slowly. The exergy outputs (W) as a function of temperature difference (°C) for the SC in Ozturk, (2007), also obtained the relationship between energy output and temperature difference $\sum o = 0.0003\Delta T^3 - 0.0403\Delta T^2 + 1.8465\Delta T - 23.43 \dots \dots \dots 10$

It can be seen that the derived relationship for the SC obtained in the present research (Eq12) $y = -0.0348\Delta T^2 + 2.4447\Delta T - 26.455$ was similar to the relationship of Ozturk, (2007). The linear and polynomial regression coefficient of determination R^2 for the SCK was 92%, satisfying the standard. It is reported Ademola, (2015), that the coefficient of determination (R^2) should be better than 75%. It is observed that the relationship between the exergy output and the temperature difference was polynomial for the SC.

$$y = 64.531 - 0.999\Delta T \dots \dots \dots 11$$
$$y = -0.0348\Delta T^2 + 2.4447\Delta T - 26.455 \dots 12$$

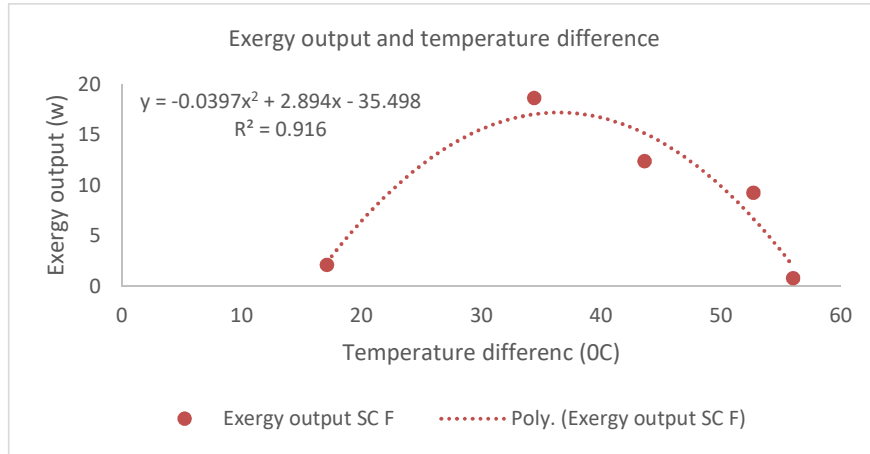


Figure 5: Exergy output and temperature difference

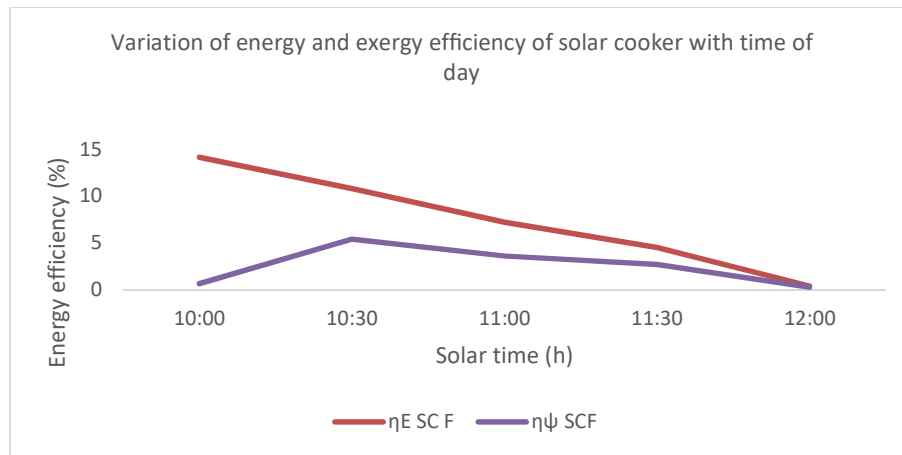


Figure 6: Variation of energy and exergy efficiency of solar cooker with time of day

The variation of the energy and exergy efficiency as a function of time for the SC is given in Fig. 6. The energy efficiency of the SC ranged from 0.29% and 10.75% during the experimental period. This is similar with the results of Todd and Miller, (2001) who found that the average efficiency for the basic cooker was 8 and 22% for cooker design tested. On the other hand, exergy efficiency of the SC ranged from 0.18% and 5.21% for the SC during the experimental period.

CONCLUSION

This experimental study was conducted to develop an energy and exergy model for predicting SC

performance in a semi-arid environment. The energy and exergy model developed was found to be useful for predicting the thermal efficiency for SC and the following conclusion were drawn:

- (1) The energy efficiency was always higher than the exergy efficiency. This is expected, because the total energy content of the hot water used as heat storage fluid is taken into account in order to calculate the energy efficiency. In other words, to calculate the energy efficiency, the quantity of the energy transferred is taken into account, and the quality of



the energy transferred is neglected.

- (2) The above-presented results indicate that the exergy efficiency of the SC was always lower than the energy efficiency at all temperatures.
- (3) It was found that the exergy efficiency for the SC varied from 0.18% and 5.21% during the experimental period. This result indicates that the SC investigated in this study is inefficient in terms of the exergy efficiency and also concluded that sensible heat energy storage systems are inherently inefficient devices in terms of the exergy efficiency.

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