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Energy and Exergy Efficiency Analysis for Solar Box Cooker with Kapook Insulator

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Abstract

This work presents evaluation of the energy end exergy efficiency of box-type solar cooker with Kapook Insulator (SCK). Thermodynamic considerations required to developed rational and meaningful methodologies for the evaluation and comparison of the efficiency of the SCK was studied. It was found that the average daily water temperature from 10:00 to 12:00 solar time was 85.02 in the SCK. The average daily temperature difference in the SCK was 43.9^{0}C. The energy output of the SC K ranged from 0.87 to 40.38W, for the time interval with an average energy output of 23.81Wfor SCK. The exergy output for the SCK ranged from 0.49 to 16.21 W, for the time interval with an average exergy output of 8.52W for SCK. 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 output at a temperature difference of 50^{o}C for the SCK was estimated to be 15.25W and 8.8Wduring the experimental period.

1. Introduction

Energy availability has a positive impact on quality of life. Long-term survival and well-being of humans and societies highly depend on access to energy [1]. In the present context, energy is considered a key issue in economic development of the nation. Annually, energy consumption increases by an average of 1% in developed countries and 5% in developing countries. Consumption of fossil fuels is dramatically growing along with the increasing world population, improvements in the quality of life, and industrialization of developing nations [2].

Deforestation in the world by the inhabitants and the emissions of certain polluting gases linked to fossil fuels (oil, etc.) have intensified the natural phenomenon of the greenhouse effect and lead to the warming of the temperature on earth. This phenomenon will have important consequences for the climate and ecosystems of the planet. The international community has therefore mobilized to propose alternatives to limit the use of forest woods and limit the concentrations of greenhouse gases in the atmosphere, with the aim of reducing emissions worldwide before 2050 [3].

Major energy needs of domestic consumers include cooking, heating and lighting. Cooking predominantly account for 36% of Nigeria's primary energy demand; hence it is necessary to meet this particular demand by using clean and efficient fuel like liquefied petroleum gas (LPG) for

cooking applications. In Nigeria, even today about 90% of rural people do not have access to modern cooking fuels and it drops to 33% in urban areas [4].
Evaluation of solar cookers requires a measure of efficiency, which is rational, meaningful and practical. The energy efficiency of a solar cooker, the ratio of the energy gained by the solar cooker to the energy originally delivered to the solar cooker, conventionally is used to measure solar cooker efficiency (efficiency = energy gained by the cooker/energy delivered from the sun to the cooker). The energy efficiency is inadequate as a measure of efficiency because it does not take into account all the considerations necessary in solar cooker evaluation. Energy efficiencies can only account for quantities of energy transferred, and can often be misleadingly high, such as in cases where heat is recovered at temperatures too low to be useful. Exergy analysis provides an alternative means of evaluating and comparing solar cookers. Exergy efficiency accounts for the temperatures associated with energy transfers to and from the solar cooker, as well as the quantities of energy transferred, and consequently provide a measure of how nearly the solar cooker approaches ideal efficiency.

Table1. 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	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 (2004)	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
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)	Energrtic and Exergetic Evaluation of Box-Type SC using different insulatin 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 eggplant using Box-Type SC	Box cooker	Performance	Determination of first and second Law efficiencies for 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

2 Methodology

2.1. Solar Box Cooker Design Considerations

The design parameters considered includes the energy requirements for cooking and daily average insolation. The energy requirement for cooking per person as explained in [12] is about 900 kJ of fuel equivalent per meal. The design of the solar box cooker constructed for this solar energy study is based on the work of [13]. A solar box cooker as reported by [14] should be sized in consideration of the largest amount of food commonly cooked and if the box needs to be moved often, it should not be so large so that this task is not too difficult. 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 [15].

2.2.Description of the Realized Solar Cooker

The thermal heat storage for solar cooking purposely design solar cooker was constructed. The cooker consists of a double wall hot box and made of ¾ ply wood sheet. 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 Kapook. The inner tray and outer box 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 tray of cooker was 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.

Three clear window glass panes with 4 mm thickness were fixed over the box. The space between these three panes of glass is critical. The air gap also acts as an insulator. A three layers glazing with 25 mm gap was used to transfer the direct radiation to the absorber trays. 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 Plate 1

Plate 1. The constructed box-type solar cooker.

2.3 Experimental Apparatus and Procedure

The experiment was conducted at Centre for Entrepreneurship and Enterprises Development (CEED) University of Maiduguri. The latitude, longitude and altitude of University campus in Maiduguri are, $11^{0}51'$ N, $13^{0}08'$ E and 354m above sea level respectively. The experiments were conducted in April 2019. During all experiments, the radiation intensity on a horizontal surface was measured using a digital pyrometer (SPM-1116SD) (accuracy 0.1W/m^2), (MTM-3801) digital thermometer with three (3) channel contact thermocouples (accuracy 0.1^{0}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 aerometer (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.

2.4. Energy and Exergy Analyses

2.4.1. Energy Analysis

Energy input is given by:

$$E_i = I_s * A_{sc} \quad \ldots\ldots (1)$$

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

Energy output is given by:

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

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).

$$\eta = \frac{Energy\ output}{energy\ input} = \frac{E_o}{E_i} \quad \ldots\ldots (3)$$

2.4.2. 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:

(Exergy)in = (Exergy)out + (Exergy)loss + 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 [10]

$$\varepsilon_i = I_b\left[1 - {}^{4T_a}/_{3T_a}\right] + I_d\left[1 - {}^{4T_a}/_{3T_s^*}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

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

The Petela [21] 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

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

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 [22]. Although the surface temperature of the sun (T_s) can be varied on the Earth' 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:

$$\varepsilon_i = \int_{T_0}^{T} MC_p\left(1 - \frac{T_0}{T}\right) dQ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (6)$$

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: $\varepsilon(T_i) = M_w C_{pw}\left[(T_{wi} - T_0) - T_0 ln\frac{T_{wi}}{T_0}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (7)$

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

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

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).

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

2.5 Comparative Analysis

The result gathered was compared using descriptive and inferential statistical methods. The energy and exergy losses were compared to the temperature difference attained during the water heating, linear regression and polynomial test.

3. Result and discussion

The cooker was set for test from 9:30am to 16:00pm. The foregoing is interpretation of the result recorded. Study on solar box cooker with natural insulating material (Kapook) has been carried out based on energy and exergy analysis Figure 1 shows the variation in the ambient temperature of corresponding insolation during the three hours' water heating test.

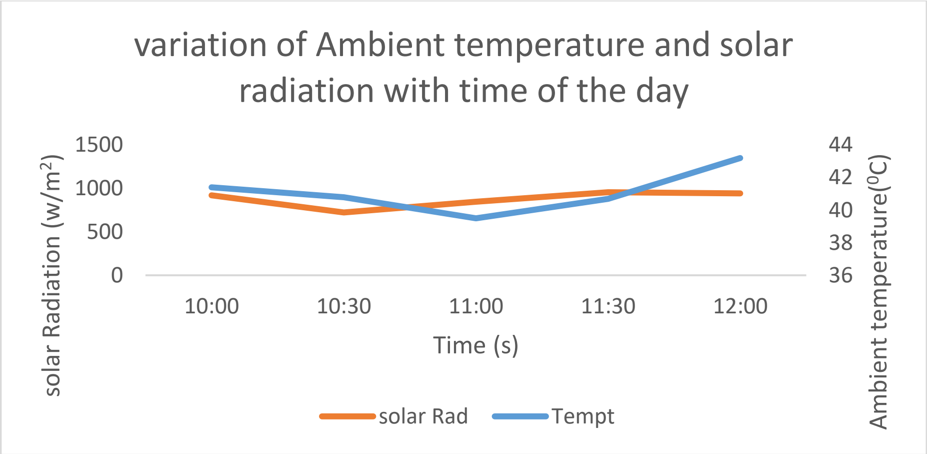

Figure 1. variation of ambient temperature and solar radiation with time of the day

The change of the water temperature in the pot for the SC K is shown as a function of time in Figure 2. The initial water temperature in the SCK was 37.1°C. The ambient temperature varied between 39.5°C and 43.2°C, whereas the solar radiation ranged from 723.5 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. Most important is that the maximum water temperature of the SCK was 98.5°C was reached after 3 hours from the start of the experiment. The result is similar to the result reported by [24].

When the average daily and maximum temperature of water in the SC was taken into account for the same time interval, the temperature rise of water in SC K was about 37.9^{0}C. This proves the efficiency of the present design for the SCK. The temperature difference in the SC K was only 18.5^{0}C at 10:10 in the morning; it reached 55.3^{0}C at 12:00 in the early afternoon. The average daily temperature difference in the SCK was 43.9^{0}C. The results showed that the SC K was able to keep the maximum water temperature in the pot 57.3^{0}C higher than the ambient temperature. Under these conditions, the SCK provided the water heating effect of 57.3^{0}C. This good performance was due to the thermal conductivity properties of the insulator of the SC K. In the present experiment the heating effect of the SCK was similar in comparison with the results obtained by [25].The temperature profiles in Figure 1 showed the same features. This is the heating effect for the SCK increased as the intensity of the solar radiation increased during the day.

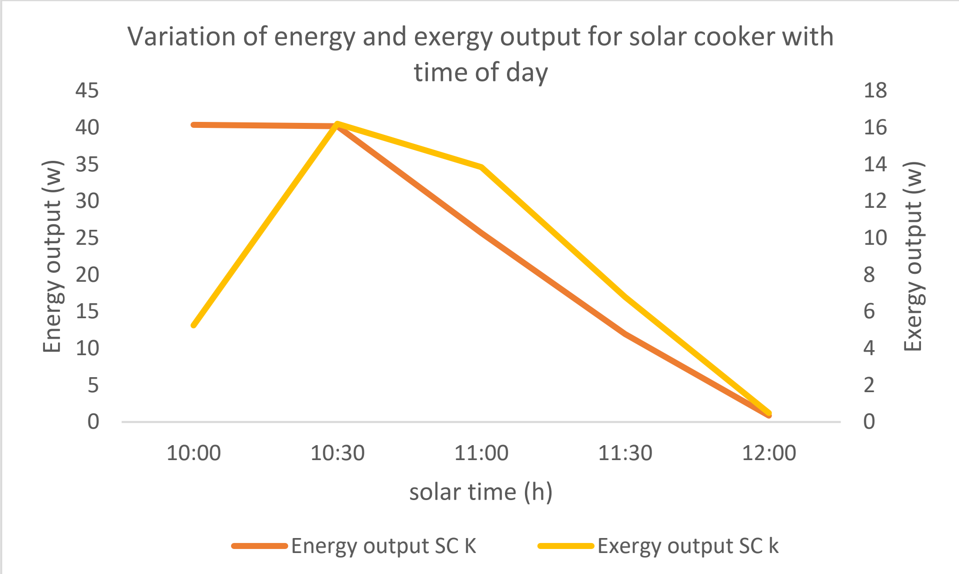

Figure 2. Variation of Energy and Exergy output for solar cooker with time of day

The energy output of the SC K (heating power) was corrected to a standard solar radiation of 700 W/m^2 by multiplying the observed energy output by 700 W/m^2 and dividing by the average solar radiation recorded during the corresponding interval. Adjusted energy output and temperature difference were calculated every 30 min for SC K. Figure 2 shows the variation of the adjusted energy and exergy output as a function of time for the SC K. The energy output of the SC K ranged from 0.87 to 40.38 W, for the period of time covered. As indicated in Figure 2, the energy output for the 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 K 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 K was 23.81W, the energy output the SC K was strongly influenced by temperature difference. The energy output for the SC K depends strongly on the water temperature, increasing considerably with this parameter. The box SC operates at lower power than most other cooking systems. [25] also reported that solar box cookers power ranges from 20 to 100 W.

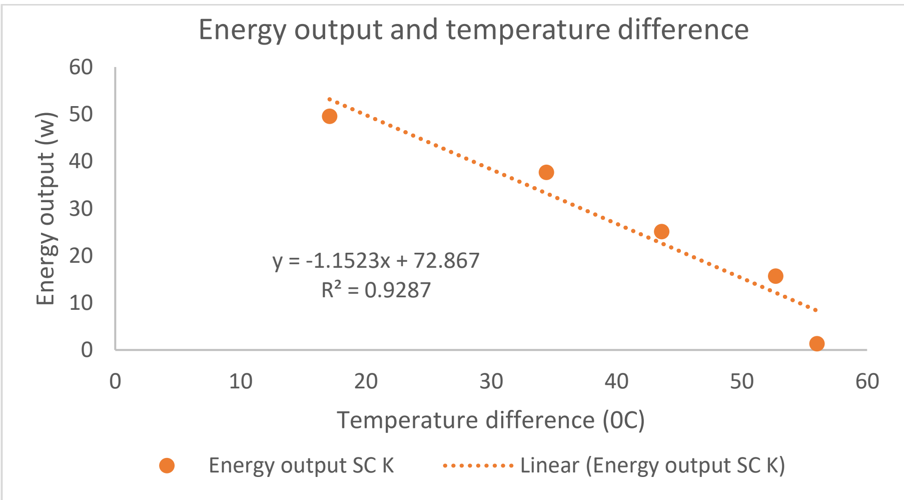

Figure 3. Energy output and temperature difference

The exergy output for the SC K is significantly different from the energy output during the water heating tests. For the period of time covered by Fig. 3, the exergy output for the SC K ranged from 0.49 to 16.21 W. The variation of the exergy output for the SC K was similar compared with the variation of the energy output. It was found that the average daily exergy output for the SC K 8.25W. The study showed that the energy output for the SC K was always greater than the exergy output. For the same time interval, the energy output for the SC K was about 65.35% more than 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 (Equation (2)).

Figure 4 represents the relationships between the energy outputs of the SC K 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 ($W/^0C$). As indicated by Figure 4, the energy output decreased as the temperature difference increased for the SC. From Figure 4 it can also be seen that the energy output of the SC K 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 K tested is given by Equation (10) with a linear regression coefficient $R^2 = 0.9287\%$. The value of energy output is calculated for a temperature difference of 50^oC using relationships determined as 15.3W. It is reported in [9] 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 50^0C using the above-determined relationships for the SC K. The energy output at a temperature difference of 50^0C was estimated to be 15.3W. The relationship between energy output and temperature difference as given by [16] is $E_o = 109.96 - 1.67\Delta T$. It can be seen that the derived relationship for the SC K obtained in the present research (Equation 9) is similar to the relationship of [16].

From Figure 5 it can also be seen that the exergy output of the SC K changes polynomially with the temperature difference. A polynomial regression of the plotted points was used to find the relationship between exergy output and temperature difference. Exergy output depending on the temperature difference for SC K tested is given by Equation (12) with a linear regression coefficient $R^2 = 0.9886\%$. The value of exergy output is calculated for a temperature difference of 50°C using the relations in Equation (13) and was determined as 9W. It is observed that the relationship between the exergy output and the temperature difference was polynomial for the SC K. In other words, 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 (^oC) for the SBC and SPC is as given by [16] which also obtained the relationship between energy output and temperature difference.

$$\sum o = 0.0003\Delta T^3 - 0.0403\Delta T^2 + 1.8465\Delta T - 23.43 \quad (11)$$

It can be seen that the derived relationship for the SC K obtained in the present research (Equation 3) is similar to the findings of [16]. The polynomial regression coefficient of determination $R^2$for the SBC was 99%, satisfying the standard. It is reported in [9] 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%. From Figure 5 it can also be seen that the exergy output of the SC K did not change linearly with the temperature difference.

$$y = 72.867 - 1.1523\Delta T \quad (12)$$
$$y = -0.0348\Delta T^2 + 2.4447\Delta T - 26.455 \quad (13)$$

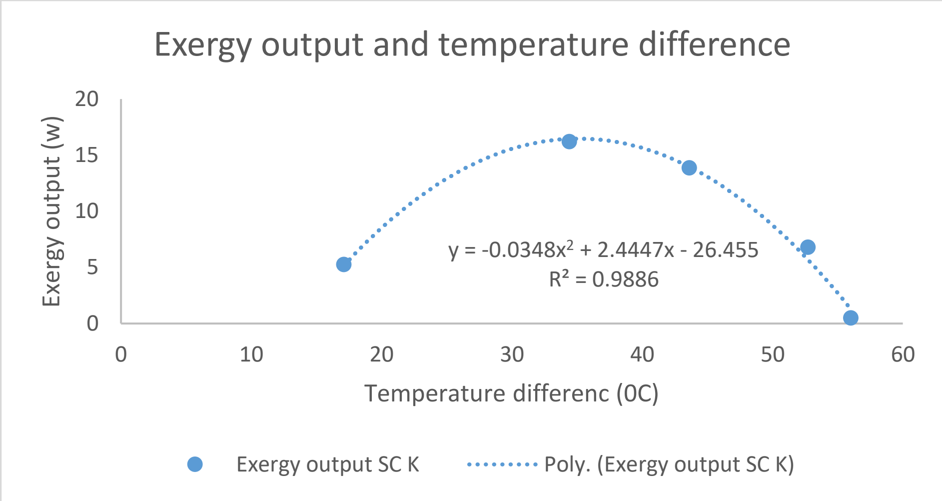

Figure 5. Exergy output and temperature difference

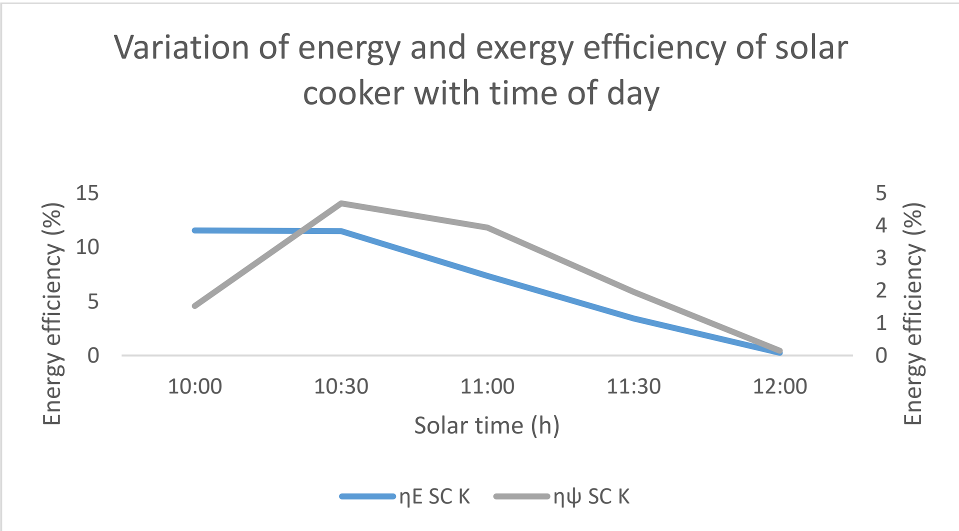

Figure 6. Variation of energy and exergy efficiency of solar cookers with time of day

The variation of the energy and exergy efficiency as a function of time for the SC K is given in Figure 6. The energy efficiency of the SCK ranged from 0.18 to 11.11%, during the experimental period. This result affirms the findings of [25], who found that the average efficiency for the basic cooker was 8 and 22%, for the best cooker design tested. For the period of time covered by Figure 4, it was found that the average daily energy efficiency for the SC K was 11.11%. The above-presented results indicated that the present SCK is well designed and its energy performance is quite efficient.

On the other hand, exergy efficiency of the SC K ranged from 0.11 to 4.52%, and the average daily exergy efficiencies for the SCK was found to be 4.52% during the experimental period.

4. Conclusion

In this paper a box solar cooker was designed, constructed and experimentally tested. The study was conducted to develop an energy and exergy model for predicting SC performance. The energy and exergy model that was developed was found to be useful for predicting thermal efficiency for SCK. This experimental efficiency study of the box type solar cooker based on energy and exergy analysis show also that the box type cooker with Kapook insulator is well suitable for preparing meals.

When the energy efficiency of the SC K is compared with its exergy efficiency, the following conclusions were: drawn: (i) 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 exergy efficiency, the quantity of the energy transferred is taken into account, and the quality of the energy transferred is neglected. (ii) The above-presented results indicate that the exergy efficiency of the SC was always lower than the energy efficiency at all temperatures. (iii) It was found that the average daily exergy efficiency for the SC K was only 4.52% during the experimental period. This result indicates that the SC K investigated in this study is inefficient in terms of the exergy efficiency. [5] also concluded that sensible heat energy storage systems are inherently inefficient devices in terms of the exergy efficiency.

Nomenclature

SC	Solar cooker
SC K	Solar cooker with Kapook insulator
SC F	Solar cooker with fibre glass insulator
Ei K	Energy input solar cooker with Kapook.
Eo K	Energy output solar cooker with Kapook.
η_E K	Energy efficiency of solar cooker with Kapook.
Ɛi K	Exergy input solar cooker with Kapook.
Ɛo K	Exergy output solar cooker with Kapook.
ψK	Exergy efficiency solar cooker with Kapook.
Ei F	Energy input solar cooker with Fibre glass.
Eo F	Energy output solar cooker with Fibre glass.
η_E F	Energy efficiency of solar cooker with Fibre glass.
Ɛi F	Exergy input solar cooker with Fibre glass.
Ɛo F	Exergy output solar cooker with Fibre glass.
ψF	Exergy efficiency solar cooker with Fibre glass.

Notation

The following symbols are used in this paper:

A = intercept area, m2;
cp = specific heat, J/kg K;
E = energy, W;
I = instantaneous solar radiation, W/m2;
m = mass, kg;
Q = heat energy, J;
T = temperature, ^{0}C;
t = time, s;
E = thermal exergy, J;
η = energy efficiency, %;
Ɛ = exergy, W;
Ɛsr = exergy of solar radiation, W/m^2; and
Ψ = exergy efficiency, %;

Subscripts

a = ambient;
b = beam;
d = direct;
e = effective diffuse radiation;
f = final;
i = input, initial;
o = output, outside;
s = sun;

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