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Energetic and Exergetic Evaluation of Box-Type Solar Cookers Using Different Insulation Materials

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***Abstract*—**The performance of box-type solar cookers has been reported by several researchers but little attention was paid to the effect of the type of insulation material on the energy and exergy efficiency of these cookers. This research aimed at evaluating the energy and exergy efficiencies of the box-type cookers containing different insulation materials. Energy and exergy efficiencies of five box-type solar cookers insulated with maize cob, air (control), maize husk, coconut coir and polyurethane foam respectively were obtained over a period of three years. The cookers were evaluated using water heating test procedures in determining the energy and exergy analysis. The results were subjected to statistical analysis using ANOVA. The result shows that the average energy input for the five solar cookers were: 245.5, 252.2, 248.7, 241.5 and 245.5J respectively while their respective average energy losses were: 201.2, 212.7, 208.4, 189.1 and 199.8J. The average exergy input for five cookers were: 228.2, 234.4, 231.1, 224.4 and 228.2J respectively while their respective average exergy losses were: 223.4, 230.6, 226.9, 218.9 and 223.0J. The energy and exergy efficiency was highest in the cooker with coconut coir (37.35 and 3.90% respectively) in the first year but was lowest for air (11 and 1.07% respectively) in the third year. Statistical analysis showed significant difference between the energy and exergy efficiencies over the years. These results reiterate the importance of a good insulating material for a box-type solar cooker.

***Keywords*—**Efficiency, energy, exergy, heating, insolation.

I. INTRODUCTION

THE daily primary energy source for cooking is fossil fuel such as coal, petroleum and natural gas. These products are not only restricted in the earth but also release gaseous or liquid pollutants during operation. According to [1], the scarcity of these energy resources and carbon dioxide concentration in the atmosphere are two major concerns of humanity. The fast-depleting traditional sources of energy, growing energy requirement and environmental pollution have forced scientists to explore alternative sources of energy [2]. Solar energy which is inexhaustible, clean and safe has being regarded as one of the most auspicious energy source to substitute for the conventional fuels for various applications including cooking. Solar cooker is an innovative way of utilizing the solar energy to cook food [3].

Energy which is a thermodynamic property can be transferred to or from a system in three forms: heat, work, and mass flow. Exergy is not simply a thermodynamic property, but a co-property of a system and the reference environment. Exergy has the characteristic that it is conserved only when all processes of the system and the environment are reversible and destroyed whenever an irreversible process occurs [4].

The traditional method of assessing and analyzing the energy disposition of an operation or system involves investigating the energy (heat) transfer and/or transformation of energy is by the completion of an energy balance. Exergy efficiencies are a measure of approach to reversibility which is not necessarily true for energy efficiencies [5]. According to [6], the three main causes of irreversibility are heat transfer between the flows, pressure losses due to fluid friction, and dissipation of energy to the environment. When an exergy analysis is performed on a solar thermal system, the thermodynamic imperfections can be quantified as exergy destruction, which is wasted work or wasted potential for the production of work. According to [7], exergy analysis is a powerful tool that has been used widely in the performance analysis of solar water heater systems. It can detect and evaluate quantitatively the maximum useful work that can be done by a solar water heater.

Reference [2] compared the energy and exergy efficiency of a community-size paraboloidal solar cooker (CSC) and a domestic-size paraboloidal solar cooker (DSC). They observed that average energy efficiency and exergy efficiency of CSC are 9.55 and 0.759% while DSC has an average energy and exergy efficiency of 25.28% and 1.964% respectively. Similarly but extensively, [8] carried out an exergy analysis of renewable energy cooking devices and reported a mean exergy efficiency of box type and paraboloid type solar cooker of 4.9 and 7.1% respectively for one litre of water and 7.9 and 10.4% respectively for two litres.

The thermal conductivity of an insulation material can be experimentally determined in a variety of ways in a laboratory. Value ranges are on the order of small fractions to thousands of W/m/ºC [9]. Various materials can be used in insulating solar cookers including: glasswool, foam, fiberglass, corkboard, wool felt, cotton, maize cob, maize husk, sawdust, paper, air, etc.

Several researchers have reported the performance of various box cookers with different insulation materials; [10] used foam as the insulating material; [11]-[16] used glasswool; [17] used glasswool and foam; [18] used paper; [18] used baton and sawdust among others.

The thermal performance of different insulation materials has been compared [19], [20] but evaluation and comparison

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of energy and exergy of solar cookers with different insulating materials is still pending thus, this research aimed at evaluating the energy and exergy analysis of solar box type solar cookers with different insulation materials

II. Methodology

A. Description of the Systems

Five flat plate collector type box solar cookers were designed and fabricated. The main distinguishing factor in the five cookers was the insulating materials used. The cookers were labeled 1-5 according to the insulation materials which were: Maize cob, Air (control), Maize husk, Coconut coir, Polyurethane foam.

Figs. 1 and 2 show the solar box cooker. Each of the five cookers has the following components:

1. Outer box: 12.5mm plywood
2. Inner box: 3mm thick hardboard, 0.36m^2 collector area
3. Insulator: 80mm thick
4. Glazing: 3mm double wall cover of tempered float glasses
5. Reflector lid: Aluminum foil
6. Absorber plate: 1.4mm gauge aluminum sheet
7. Cooking pot: 1.5mm gauge aluminum sheet

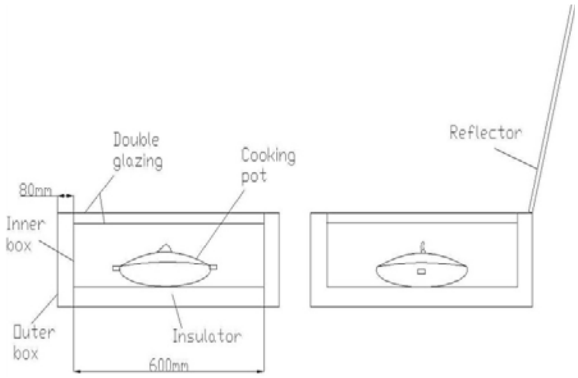

Fig. 1 Schematic diagram of the solar box cooker

Fig. 2 A solar box cooker

B. Experimental Set up and Instrumentation

The experiments were conducted at Department of Agricultural and Environmental Engineering, University of Ibadan, Ibadan Oyo State, Nigeria located at 7.4417^{o}N and 3.9000^{o}E. The five box solar cookers were set up under the sun at a location free from obstruction and shadows as shown in Fig. 3.

The solar cookers were oriented to face the direction of the sun. The orientation of the cooker was in such a way that the lid of the reflector was set normal to the rays of the sun. Thermocouples which were attached to digital multi-meters were placed inside the pot to monitor the temperature. Thermometers were placed in the surroundings to monitor the ambient temperature around the cookers. A solar meter was also oriented to face the direction of the sun's rays so as to measure the total horizontal insolation.

1.5 litres of water was loaded into the pots of each cooker. The water temperature inside the pots, ambient temperature and solar insolation were monitored and recorded at 10 minutes interval as required by standard S580 of [21]. This experiment was initially carried out during a three hour period. It was later carried out over three consecutive years

Fig. 3 Experimental set up

C. Evaluation of Energy and Exergy Efficiency

1. Energy Analysis

Energy Input

Energy input was calculated using (1):

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

where I_s is the solar radiation: A_{SC} is area of aperture of solar cookers.

Energy Output

Energy output was calculated with (2):

$$E_o = \frac{m_w . C_{pw}(T_{wf} - T_{wi})}{\Delta t} \quad (2)$$

where m_w is mass of water: C_{pw} is specific heat of water: T_{wf} is final temperature of water: T_{wi} is initial temperature of water: Δt is time difference.

Energy Efficiency

The energy efficiency of the solar cooker was calculated as the ratio of the energy gained by the solar cooker (energy output) to the energy of the solar radiation (energy input) as given in (3).

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

2. Exergy Analysis

Exergy in

The availability (exergy) of a solar flux with both beam and diffuse components was computed using (4):

$$Ex_i = I_s\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] A_{sc} \quad (4)$$

where E_{xi} is the exergy of solar radiation: T_a is the ambient temperature (K): T_s is the sun temperature (5800 K): $I_s$is the solar radiation (W/m^2): A_{SC} is area of aperture of solar cookers

Exergy out

When the temperature of water is increased from T_{wi} to temperature T_{wf}, the exergy was calculated using (5):

$$Ex_o = m_w.C_{pw}\left[(T_{wf} - T_{wi}) - T_a \ln\left(\frac{T_{wf}}{T_{wi}}\right)\right]/\Delta t \quad (5)$$

where m_w is mass of water: C_{pw} is specific heat of water: T_{wf} is final temperature of water: T_{wi} is initial temperature of water: Δt is time difference.

Exergy Efficiency

The exergy efficiency of the solar cooker was computed as the ratio of the exergy gained by the solar cooker (exergy output) to the exergy of the solar radiation (exergy input) using (6):

$$\psi = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{Ex_o}{Ex_i} = \frac{m_w.C_{pw}\left[(T_{wf}-T_{wi})-T_a\ln\left(\frac{T_{wf}}{T_{wi}}\right)\right]/\Delta t}{I_s\left[1+\frac{1}{3}\left(\frac{T_a}{T_s}\right)^4-\frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]A_{sc}} \quad (6)$$

D. Comparative Analysis

The results gathered were compared using descriptive and inferential statistical methods. The energy and exergy losses were compared to the temperature difference attained during the water heating test. Analysis of variance (ANOVA) was carried out for the energy and exergy efficiencies at 0.05 significance level to investigate significant differences between the solar cookers over the years.

III. Results and Discussion

Fig. 4 shows the variation in the environmental conditions during the three hours water heating test.

Energy Analysis

The energy efficiency during a three hour water heating test is as shown in Fig. 5. It reveals that cooker 1 and cooker 4 had the highest efficiencies. The average energy input for solar cookers 1, 2, 3, 4 and 5 over the three years period are: 245.5, 252.2, 248.7, 241.5 and 245.5J respectively while their respective average energy losses are: 201.2, 212.7, 208.4, 189.1 and 199.8J. The average energy efficiencies for the solar cookers are shown in Fig. 6. It was observed that the energy efficiency of the solar cooker reduced along the years. The result shows that cooker 4 (i.e. insulated using coconut coir) has the highest energy efficiency even though it also reduced along the years. Fig. 4 shows that cooker 2 (insulated with air) has the lowest energy efficiency. It was discovered that energy losses increases with increase in temperature difference up to a peak value before reducing almost linearly with further increase in the temperature difference as presented in 5. The reduction in the energy loss after attaining a peak value was observed to be lowest for cooker 2. The result of the energy analysis is comparable to that of a double exposure box-type solar cooker insulated with glass wool reported by [22] with an efficiency ranging from 14.35-34.77% for different cooking vessels.

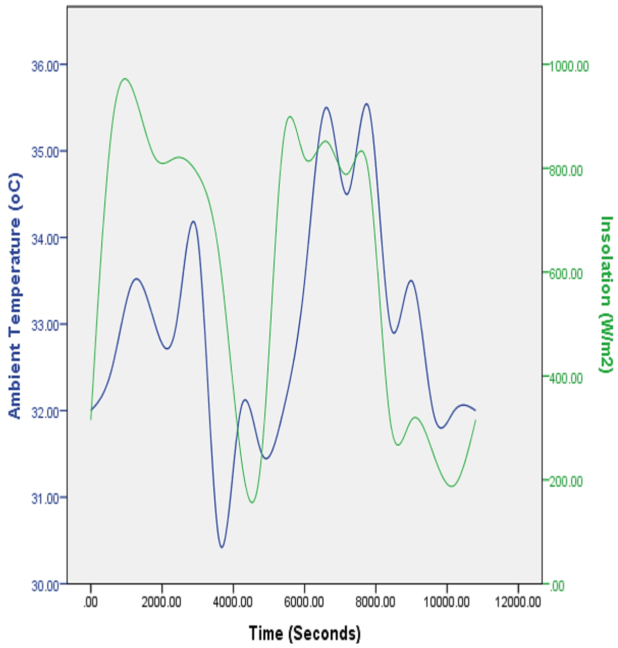

Fig. 4 Variation in ambient temperature and insolation during the three hours water heating test

Further statistical analysis using ANOVA reveals that there was significant difference between the energy efficiencies of the solar cookers over the years but no significant different was observed between the cookers. This result is as shown in Tables I and II.

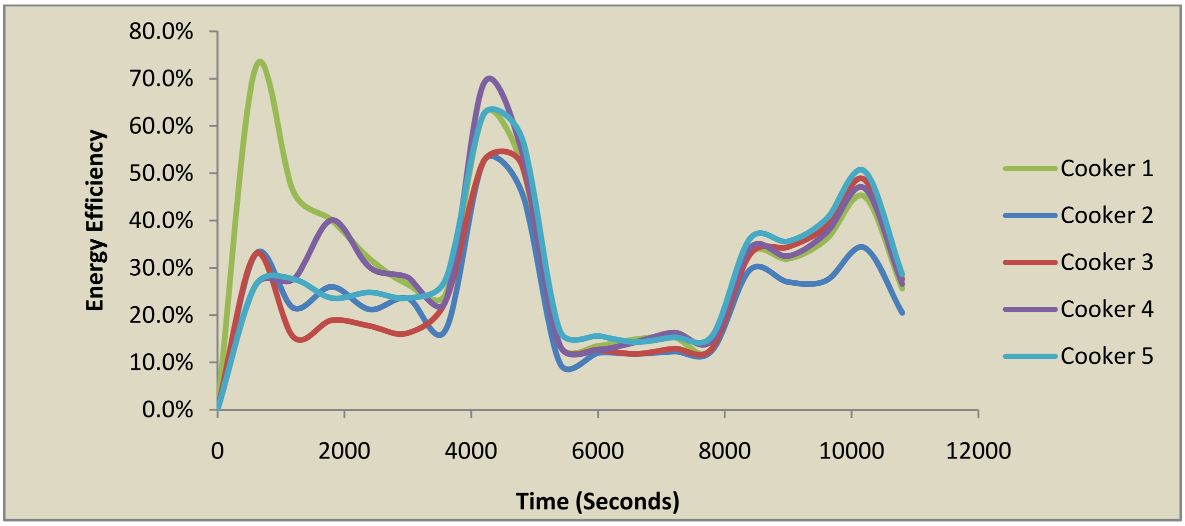

Fig. 5 Energy efficiency of solar cookers during a three hour water heating test

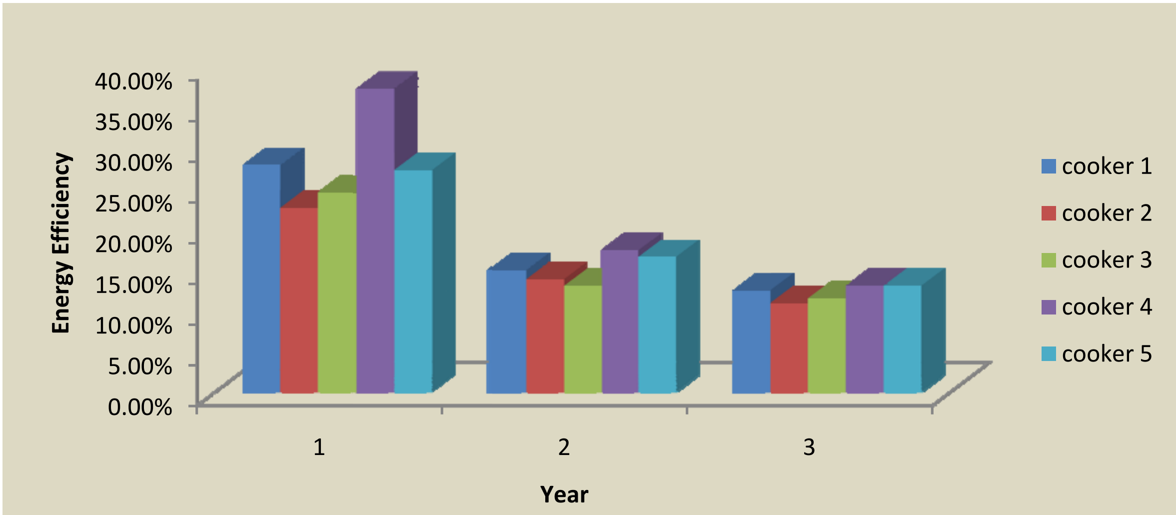

Fig. 6 Average energy efficiency of solar cookers

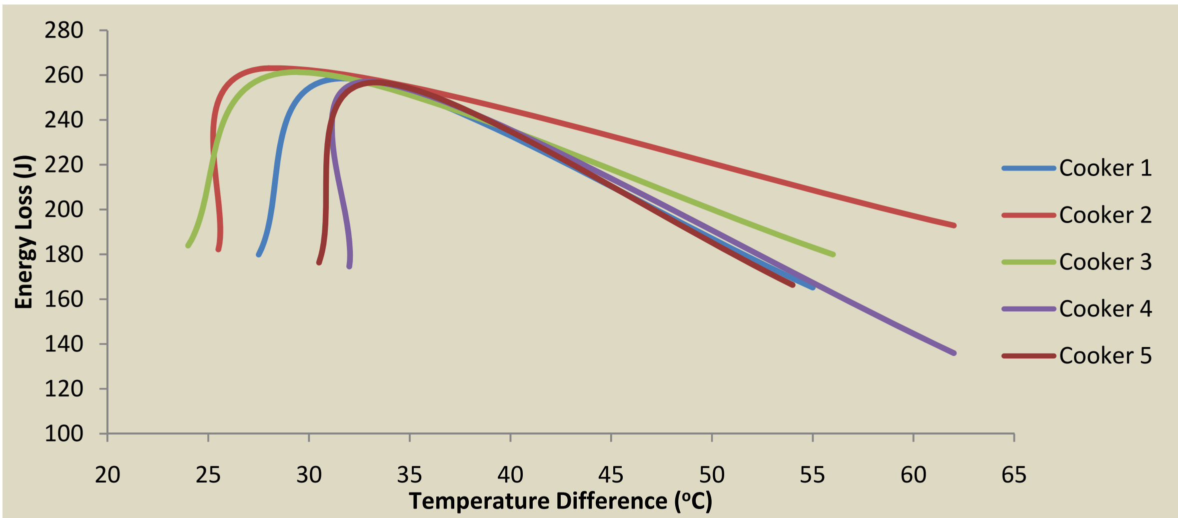

Fig. 7 Variation of energy loss of solar cookers with time difference

TABLE I
ANOVA RESULT FOR ENERGY EFFICIENCIES OF SOLAR COOKERS (SOURCE OF VARIATION: YEARS)

Source of Variation	SS	df	MS	F	P-value	Significance at 0.05
Between Years	0.069057	2	0.034528	28.39335	2.82E-05	Significant
Within each year	0.014593	12	0.001216			
Total	0.08365	14				

TABLE II
ANOVA RESULT FOR ENERGY EFFICIENCIES OF SOLAR COOKERS (SOURCE OF VARIATION: SOLAR COOKERS)

Source of Variation	SS	df	MS	F	P-value	Significance at 0.05
Between Cookers	0.008726	4	0.002182	0.291179	0.87713	Not Significant
Within each cooker	0.074923	10	0.007492			
Total	0.08365	14				

Exergy Analysis

The exergy efficiencies during the three hours water heating test are shown in Fig. 8. Cooker 4 had the highest efficiency of around 7%. The average exergy input for the five solar cookers are: 228.2, 234.4, 231.1, 224.4 and 228.2J respectively while their respective average exergy losses are: 223.4, 230.6, 226.9, 218.9 and 223.0J. From the result, it was also observed that the exergy efficiency of the solar cooker reduced along the years. The result shows that cooker 4 has the highest exergy efficiency even though it also reduced along the years. Fig. 9 shows that cooker 2 has the lowest exergy efficiency although it was slightly higher than cooker 3 in the second year of use. From the result presented in Fig. 10, it was discovered that exergy losses increases with a little increase in temperature difference up to a peak value before reducing almost linearly with further increase in the temperature difference. The reduction in the exergy loss after attaining a peak value was observed to be lowest for cooker 2. Reference [2] observed low exergy efficiency (a maximum of 1.964% for DSC). According to them, the exergy efficiency of any solar cooker or solar thermal device is very low because input solar radiation is rich in exergy and being utilized in the form of heat at low temperature.

Statistical analysis using ANOVA reveals that there was significant difference between the exergy efficiencies of the solar cookers over the years but no significant different was observed between the cookers at 0.05 level of significance. This result is as shown in Tables III and IV.

TABLE III
ANOVA RESULT FOR EXERGY EFFICIENCIES OF SOLAR COOKERS (SOURCE OF VARIATION: YEARS)

Source of Variation	SS	df	MS	F	P-value	Significance at 0.05
Between Years	0.000817	2	0.000408	22.30985	9.06E-05	Significant
Within each year	0.00022	12	1.83E-05			
Total						

TABLE IV
ANOVA RESULT FOR EXERGY EFFICIENCIES OF SOLAR COOKERS (SOURCE OF VARIATION: SOLAR COOKERS)

Source of Variation	SS	df	MS	F	P-value	Significance at 0.05
Between Cookers	0.000171	4	4.28E-05	0.494808	0.740256	Not Significant
Within each cooker	0.000865	10	8.65E-05			
Total						

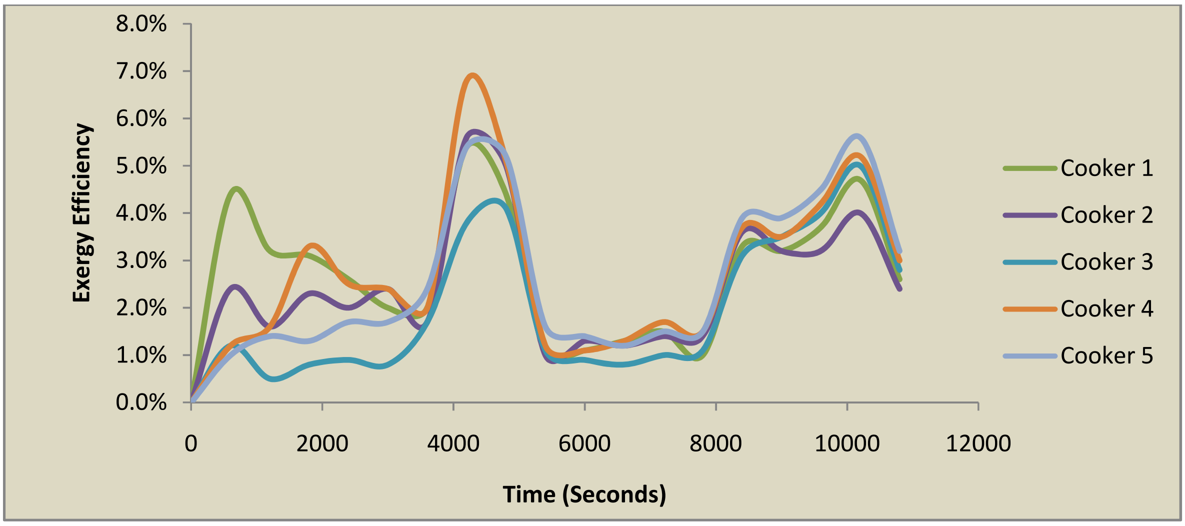

Fig. 8 Exergy efficiency of solar cookers during a three hour water heating test

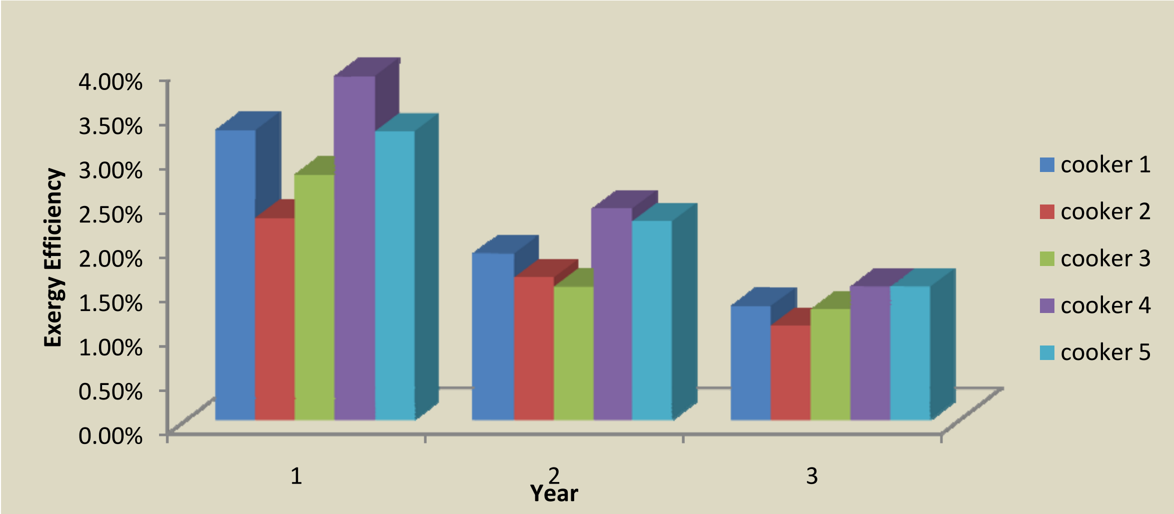

Fig. 9 Average exergy efficiency of solar cookers

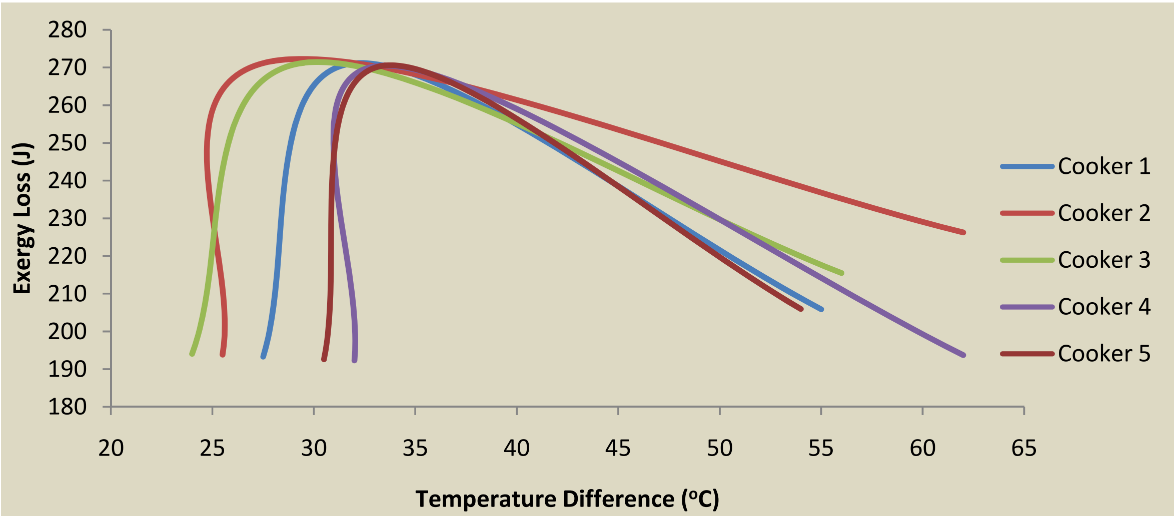

Fig. 10 Variation of exergy loss of solar cookers with time difference

IV. Conclusion

Energy and exergy analysis has been performed for five box solar cookers with different insulation materials. The solar cooker with air as an insulator performed poorly when compared to others. This paper further reiterates the importance of insulation materials in a box solar cooker. A good insulation material is required to reduce the interaction between the solar cooker and the environment – reducing energy and exergy losses. Despite the similarity in the performance of the different insulators, coconut coir was found to give a better energy and exergy efficiency.

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