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Comparative experimental study of solar cookers using exergy analysis

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Abstract This communication presents the comparative experimental study of solar cookers based on the exergy analysis. In this study two different types of solar cookers viz. paraboloid type and box type have been evaluated using exergy analysis. The experiments have been carried out with cookers filled with different volume of water viz. one and two liters along with the suitable quantity of rice. Data of temperatures and solar radiation have been measured for different food stuff on clear sky day of the month. It is found that the exergy efficiency increases as the volume of water increases, however, the exergy efficiency of paraboloid solar cooker is found to be higher than that of the box-type solar cooker for all the cases mentioned above. However, it is also found that the exergy efficiency vary with the cooking stuff and water which is due to the fact that the requirement of heating vary with the food stuff.

Keywords Box and paraboloid type solar cookers · Solar radiation · Exergy efficiency · Food cooking

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List of symbols

A_{sc}	Area of collector (m^2)
C_{pw}	Specific heat of water (kJ/kg-K)
I_b	Beam radiation (W/m^2)
I_d	Direct radiation (W/m^2)
m_w	Mass of water (kg)
T_a	Ambient temperature (°C)
T_s	Sun temperature (°C)
T_s^*	Effective diffuse radiation temperature (°C)
T_{wi}	Initial water temperature (°C)
T_{wf}	Final water temperature (°C)
ε	Thermal exergy at temperature T
$\varepsilon(T_i)$	Thermal exergy at temperature T_i
Ξ_o	Exergy output (W/m^2)
Ξ_i	Exergy input (W/m^2)
η_{ex}	Exergy efficiency

Introduction

Solar energy is one of the most promising renewable energy resources which is available in most of the developing countries including India. Solar thermal is being developed and disseminated in many countries around the world. The Ministry of New and Renewable Energy (MNRE), Govt. of India has been pursuing a comprehensive program in the country on the development and dissemination of renewable energy technologies. There are basically two types of solar cooker one is box-type solar cooker and other is paraboloid concentrating type solar cooker. Paraboloid type solar cooker can cook food in lesser time than that of box-type solar cooker. Solar cooking saves not only fossil fuels but also keeps the environment free from pollution without hampering the nutritional value of the food. Cooking is one of the most important activities for people all over the world. The problem arises when fuel is either scarce or highly expensive. The problems are encountered more pronounced in most developing countries, particularly in remote and rural areas. Cooking accounts for a major share of energy consumption in developing countries. As the authors know 70% population of India lives in rural areas and there are about 300 sunny days a year in India. Cooking in a rural area mainly depends upon conventional energy sources such as cow dung, straw, wood, coal and hence, solar cooking can play an important role in rural areas in cooking. Solar cookers are the most promising devices since firewood used for coking causes deforestation while commercial fuels such as LPG and electricity are not available besides, the cow dung and agricultural wastes used for cooking are good fertilizers. In this way, solar cooking may be helpful to bring prosperity besides, saving the conventional energy resources.

The International standard procedure for testing solar cookers and reporting performance was proposed at the Third World Conference on Solar Cooking (Avinashilingam University, Coimbatore, India, 6–10 January, 1997) and revised by the committee over the following months [1]. The standard proposed by Mullick et al. [2] is more complicated and less universal than the one being evaluated, though the characteristic curve they developed is a good predictive tool. Grupp et al. [3] employ a test procedure that presents much useful information especially for Europe. In recent years several authors have investigated methodologies for the evaluation and comparison of solar cookers [1–5]. Traditional methods of characterizing the performance of solar cookers are based on energy analysis [6–8]. This analysis, in turn, is based on the first law of thermodynamics and provides information about the quantity of energy without investigating the quality and the availability of energy.

Buddhi and Sahoo [9] designed a box-type solar cooker having latent heat storage and showed that it is possible to cook the food, even in the evening hours with latent heat storage. Nahar [10] designed, developed and tested a novel solar cooker that does not require any tracking and its performance has been compared with a hot-box solar cooker. The overall efficiency of the novel solar cooker has been found to be 29.5% and the payback period found between 1.30 and 3.29 years depending upon the fuel it replaces. Gaur et al. [11] made a performance study of the box-type solar cooker with special emphasis on the shape of lid of the utensils used. The study revealed that the performance of a solar cooker could be improved if a utensil with a concave shape lid is used instead of a plain lid generally provided with the solar cookers. Buddhi et al. [12] analyzed the thermal performance of a box-type solar cooker on the basis of first and second figure of merit with and without load, respectively, and found that the second figure of merit depends on the quantity of water loaded in the solar cooker and hence, the performance of the test method should specify the amount of water to be taken.

Al-Soud et al. [13] designed, constructed, operated, and tested a parabolic solar cooker with automatic two axes sun tracking system to overcome the need for frequent tracking and standing in the sun, facing all concentrating solar cookers with manual tracking, and a programmable logic controller was used to control the motion of the solar cooker. It is found that the proposed parabolic solar cooker demonstrated its ability to heat water inside the cooker's tube to 90 °C in typical summer days, where the maximum registered ambient temperature was 36 °C. Mawire et al. [14] worked on mathematical models for thermal energy storage (TES) system and a thermal energy utilization (TEU) system of an indirect solar cooker and have been used to perform discharging simulations in an indirect solar cooker. Discharging results of the TES system are presented using two different methods. The first method discharges the TES system at a constant flow-rate while the second method varies the flow-rate in order to maintain a desired power at a constant load inlet temperature. The results of discharging the TES system at a constant flow-rate indicate a higher rate of heat utilization. This is not beneficial to the cooking process since the maximum cooking temperature is not maintained for the duration of the discharging period. On the other hand, the controlled load power discharging method has a slower initial rate of heat utilization but the maximum cooking temperature is maintained for most of the discharging process which is desirable for the cooking process.

Exergy analysis, on the other hand, is based on the second law of thermodynamics which not only considers the irreversibility in a system but also it is directly related to the quality of the available energy. Exergy is defined as the maximum work, which can be produced by a stream or system for a specified environmental condition, especially the ambient temperature. In many instances, energy-based performance measures can be misleading, and that exergy-based performance measures provide a more realistic evaluation of thermodynamic systems in general [15–18]. Energy efficiency can only account for quantity of energy transferred, and can often be misleading high, however, exergy efficiency tells about the quality of energy. Exergy analysis provides an alternative means of evaluating and comparing the solar cookers. Exergy efficiency is a measure of the entropy generation or exergy destruction within the system. Exergy efficiencies account for the temperatures associated with energy transfers to and from solar cookers, as well as the quantities of energy transferred, and consequently provide a measure of how nearly solar cooker approach ideal efficiency.

Petela [19] analysed the simple solar parabolic cooker (SPC), of the cylindrical trough shape, using exergy analysis for the first time and found that the exergy efficiency of the SPC is relatively very low (1%), and to be about 10 times smaller than that of the energy efficiency. Mawire et al. [20] worked on the charging of oil–pebble bed thermal energy storage (TES) system for a solar cooker and analysed the simulated energy and exergy. Energy and exergy analyses are carried out using two different charging methods to predict the performance of the TES system. The first method charges the TES system at a constant flow rate. In the second method, the flow rate is made variable to maintain a constant charging temperature. Energy efficiencies using both methods are comparable whilst the constant-temperature method results in greater exergy efficiency at higher levels of the solar radiation. Mukaro and Tinarwo [21] designed and constructed and evaluated a hot-box reflector solar cooker using a microcontroller-based measurement system. They [21] found that peak temperatures of about 90 °C for the food can be attained in about 5 h on a clear day in Bindura, Zimbabwe (18°S, 31°E). A standardized cooking power of 11 W and an overall efficiency of 15% were found for this cooker.

In this study two different types of solar cookers viz. box type and paraboloid type has been investigated and attempt has been made to compare the experimental performance of the two based on the exergy analysis. The experiment has been carried out on clear sky days of different months of a year with both the cookers filled with different volume of water and rice. It is found that the exergy efficiency of paraboloid type solar cooker is higher than that of the box type cooker.

Experimental set-up and procedure

This experimental study deals with the comparative performance based on exergy analysis of two different types of solar cookers viz. box type and paraboloid type as shown in Figs. 1 and 2a, b. The experiment has been carried out during the clear sky day for different months in year using

Fig. 1 Photographic view of experimental set-up

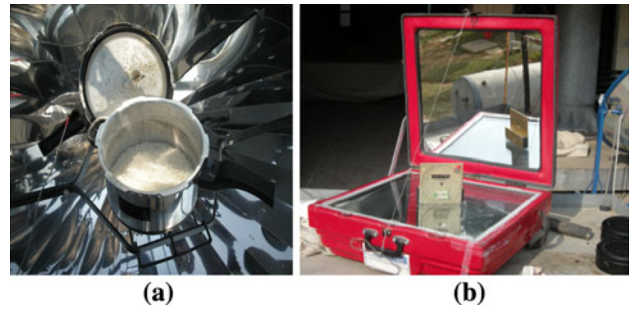

Fig. 2 **a** Paraboloid cooker with food stuff and **b** the photographic view of box-type solar cooker

water and different foods as the cooling items and the exergetic efficiency of the two types of solar cooker has been compared in the study. Experiment has been done with one and two liters of water along with 250 g of rice in both types of cookers. Before starting the experiment, some measurements like dimensions and mass of water has been measured. On the basis of measured dimensions, the area of aperture for both types of solar cookers has been calculated. Firstly, the cover plate and reflector of both types of solar cookers have been properly cleaned and then it is brought outside in the sunlight. In the case of box type cooker, the cooking pot was kept inside the solar cooker and in the case of paraboloid type cooker, the cooking pot was placed on the stand at the focal point of the parabolic concentrator so that the reflected rays fall at its base and both the cookers were places due to south. After completing the necessary requirements, the predefined amount of water in cooking pot has been taken. A thermocouple wire for the measurement of water temperature inside the cooking pot at regular periodic intervals has been inserted through a hole in the lid of pressure cooker. The thermocouple is inserted in such a way that one end of it remains immersed in the water without touching the walls of the bottom of the pot and the other end is connected to digital temperature sensor at different channels in both the cases. One more T-Type thermocouple is connected to digital temperature indicator to measure the ambient temperature.

A pyranometer for measuring intensity of solar radiation is mounted on the outer frame of the paraboloid type in such a manner that no shadow cast on the exposed area of the dish, normal to the direction of the plane of aperture and is connected to a data logger. Tracking of the dish has been carried out manually at every 5 min to insure that the dish remains normal to the sun with the motion of the sun. In the case of paraboloid type cooker, cooking pot in the tray is adjusted in such a way that the bright spot of the sun rays is positioned at the bottom of the cooking pot. Measurements of ambient temperature (T_a), water temperature in the cooking pot (T_W), intensity of direct solar radiation on the aperture plane of the parabolic concentrating solar cooker (I_b) have been recorded at an interval of 5 min during cooking of food stuff. As the water reaches its stagnation temperature during heating, the parabolic reflector and box type reflectors is shaded by turning it in the opposite direction and covering it by a black cloth to insure blockage of solar radiation.

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:

$$(\text{Exergy})_{\text{in}} = (\text{Exergy})_{\text{out}} + (\text{Exergy})_{\text{loss}} + \text{Irreversibility} \tag{1}$$

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 [22]:

$$\Xi i = I_b\left[1 - {}^{4T_a}\!/_{3T_s}\right] + I_d\left[1 - {}^{4T_a}\!/_{3T_s^*}\right] \tag{2}$$

where Ξi is the exergy of solar radiation (W/m^2); I_b is the intensity of beam radiation (W/m^2); I_d is the intensity of direct radiation (W/m^2); T_a is the ambient temperature (K); T_s is the sun temperature (K); and T_s^* is the effective diffuse radiation temperature (K).

The Petela [23] 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.,

$$\Xi i = i\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]A_{SC} \tag{3}$$

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 [24]. 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:

$$\varepsilon = \int_{T_0}^{T} m.C_p\left(1 - \frac{T_O}{T}\right)dQ \tag{4}$$

Equation 4 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:

$$\varepsilon(T_i) = m_w.C_{pw}\left[(T_{wi} - T_o) - T_o \ln\frac{T_{wi}}{T_o}\right] \tag{5}$$

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

$$\Xi_o = m_w.C_{pw}\left[(T_{wf} - T_{wi}) - T_a \ln\frac{T_{wf}}{T_{wi}}\right]\Big/\Delta t \tag{6}$$

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 [25, 26]. 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).

$$\eta_{ex} = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{\Xi_o}{\Xi i} = \frac{m_w \cdot C_{pw}\left[(T_{wf} - T_{wi}) - T_a \ln\frac{T_{wf}}{T_{wi}}\right]\Big/\Delta t}{i\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]A_{SC}} \tag{7}$$

Results and discussion

Comparative study on two different types of solar cookers viz. paraboloid type and box type has been carried out based on exergy analysis. Figures 3 and 4 illustrate the variation of efficiency and solar radiation with respect to time for one and two liters (L) of water in the paraboloid solar cooker. From Figs. 3 and 4 it is found that initially the efficiency is high and then decreases as the time increases and reaches the stagnant level as the water temperature approaches the optimum level, i.e., near to boiling point. Initially efficiency is high due to the fact that change in temperature of water inside the cooker is quick and so as the temperature difference is more. From Eq. 6 it is clear that output exergy is directly proportional to temperature difference, therefore initially output exergy will also be high, however, initially input exergy is low which is due the fact that input exergy is directly proportional to incident radiation (equation-3) which is low initially. Therefore, output to input ratio is high as a result instantaneous efficiency is found to be higher initially. On the other hand, the solar (energy) radiation has a different trend with time which can be seen from Figs. 3 and 4. The solar intensity has increasing trend in the first half, while it is having reverse trend in the second half. Therefore, the output to input ratio viz. the efficiency of the solar cooker decreases in the afternoon. This is also due to the fact that the temperature difference near boiling point increases slowly while solar radiation also. As a result it was find the results shown in Figs. 3 and 4.

Figures 5 and 6 illustrate the variation of exergy efficiency, i.e., second law efficiency and solar radiation with respect to time for one and two liters of water in box-type solar cooker. From these figures it is found that initially

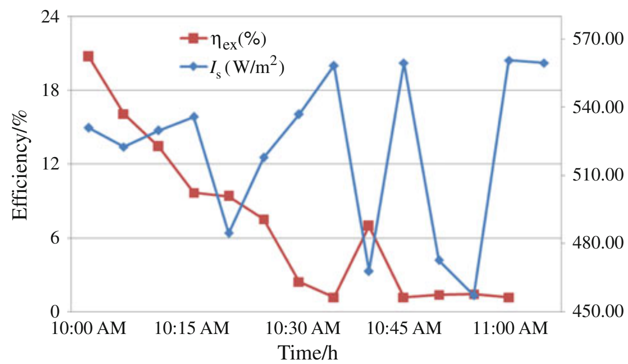

Fig. 3 Time versus efficiency and solar radiation for 1 L of water in paraboloid solar cooker

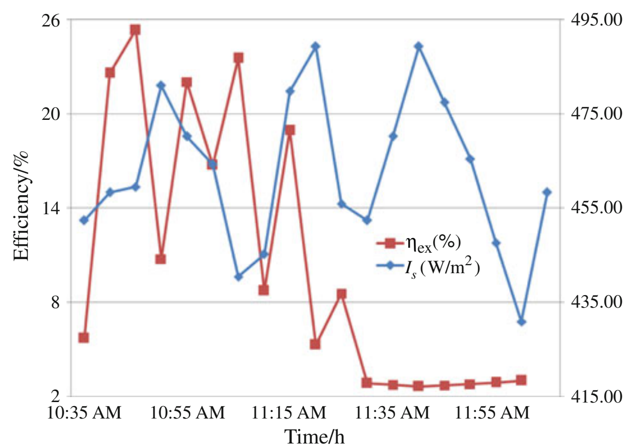

Fig. 4 Time versus efficiency and solar radiation for 2 L of water in paraboloid solar cooker

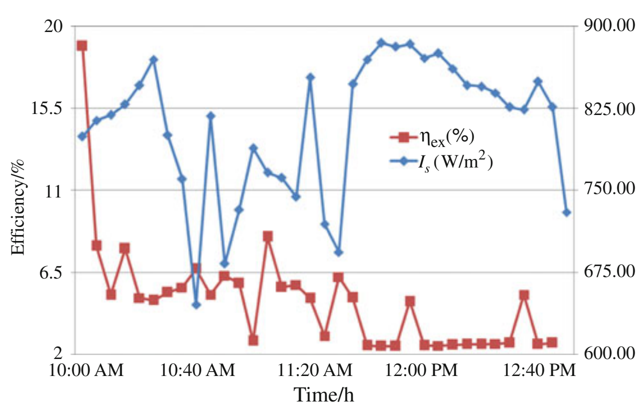

Fig. 5 Time versus efficiency and solar radiation for 1 L of water in box-type solar cooker

efficiency is high and then decreases as the time increases and reaches to approximately stagnant level as the temperature reaches near to boiling point, this variation in exergy efficiency with respect to time is explained above, however, there is fluctuation in efficiency which is due to

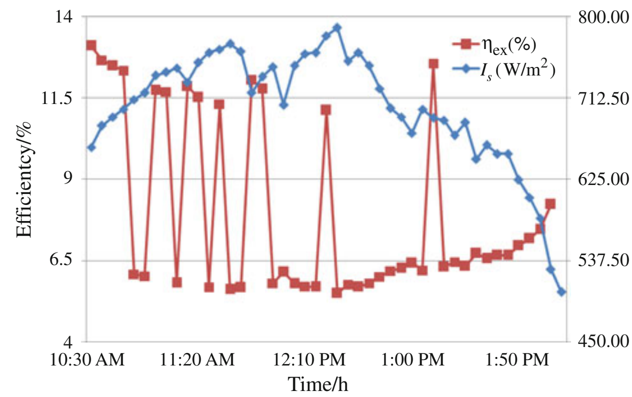

Fig. 6 Time versus efficiency and solar radiation for 2 L of water in box-type solar cooker

fluctuating nature of solar radiation which can be seen from Figs. 5 and 6. Mean exergy efficiency of box type and paraboloid type solar cooker in case of one liter of water is 4.9 and 7.1%, respectively, and in case of two liters of water it is 7.9 and 10.4%, respectively. Therefore, it is found that exergy efficiency of paraboloid solar cooker is higher than the box type solar cooker.

Figures 7 and 8 illustrate the variation of efficiency and solar radiation with respect to time for 250 g (gms) of rice in both types of solar cookers as mentioned above. From the Fig. 7 it is found that, initially as the time increases efficiency increases takes the peak and then decreases and reaches to stagnant level, however, from Fig. 8 it is found that initially efficiency is high then decreases and reaches to stagnant level as the time increases. As far as solar radiation concern it increases with respect to time takes the peak and then decreases which can be seen from Figs. 7 and 8. Owing to this nature of solar radiation initially temperature increases slowly and then increases sharply takes the peak and then decreases, therefore initially temperature difference is small then large and as temperature reaches to stagnant level again it is small. From Eq. 6, it is

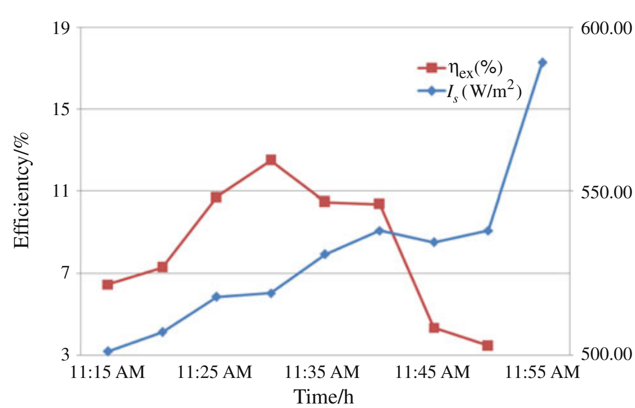

Fig. 7 Time versus efficiency and solar radiation for 250 g rice in paraboloid solar cooker

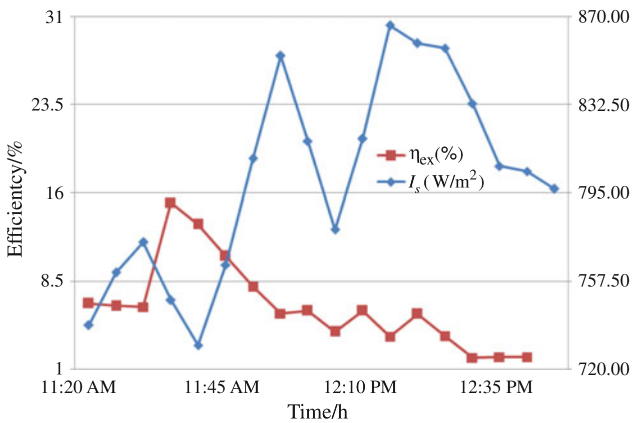

Fig. 8 Time versus efficiency and solar radiation for 250 g rice in box-type solar cooker

clear that output exergy is directly proportional to temperature difference; therefore it changes with respect to time so as the exergy efficiency changes. Exergy efficiency with 250 g of rice of box type and paraboloid type solar cooker is 6.3 and 8.2%, respectively; therefore in this case also exergy efficiency of paraboloid type cooker is higher than that of box type cooker.

The physical significance of the results is that exergy, i.e., the quality of energy and/or availability of energy which can be calculated by second law of thermodynamics is always less than the quantity of energy based on first law of thermodynamics and/or simply the principle of conservation of energy. The results obtained in this study as given in Figs. 3, 4, 5, 6, 7, 8 clearly shows that the efficiency of solar cooker is quite low which is the obvious case and can be explained in terms of irreversibilities associated with these systems. However, the results obtained and shown in this study exhibits better result than those obtained by earlier authors [15–17]. This is basically due to the fact that the system is modified and all the precautions have been taken into consideration to reduce heat/energy losses. Besides, due to the technological advancement especially in the reflector and absorber plates/materials the authors get better performance for both types of cookers than those obtained by earlier authors given in Refs. [15–17]. Thus, this article gives better result and hence, these modified solar cookers can perform better to fulfill the requirements of these renewable energy-based systems for real life applications for both rural and remote areas around the world in general and for India in particular.

As can be seen from literature studies on solar cooker has been carried out using energy and exergy analysis [6–12, 15–17, 19]. For example, Buddhi and Sahoo [9] designed a box-type solar cooker having latent heat storage and showed its importance in evening hours or when there is no availability of sun. Gaur et al. [11] made a performance study of the box-type solar cooker with special emphasis on the shape of lid of the utensils used and found that cooker could be improved if a utensil with a concave shape lid is used. Buddhi et al. [12] analyzed the thermal performance of a box-type solar cooker on the basis of first and second figure of merit with and without load, respectively, and found that the second figure of merit depends on the quantity of water loaded in the solar cooker. Petela [19] analysed the simple solar parabolic cooker (SPC), of the cylindrical trough shape, using exergy analysis and found that the exergy efficiency of the SPC is relatively very low as compared to energy efficiency. Mawire et al. [20] worked on the charging of oil–pebble bed thermal energy storage (TES) system for a solar cooker and analyzed the simulated energy and exergy. On the other hand, few studies have been carried out on design and development of different cookers [10, 13]. But none of the authors as mentioned above compared the solar cookers viz. paraboloid type and box-type performance based on exergy analysis which is our case therefore, the study is new of this kind.

Conclusions

This experimental study deals with the comparative performance study of two different types of solar cookers viz. paraboloid type and box type based on exergy analysis. From the study following conclusions have been drawn:

- Initially exergy efficiency is high then decreases sharply and then slowly decreases and reaches to stagnant level which is due to the fact that, initially temperature difference is high and decreases with respect to time and reaches to constant level when it is near to boiling point. On the other hand, solar radiation has different trend with time which is initially low then increases sharply takes peak and then decreases.
- Mean exergy efficiency with one and two liters of water of paraboloid type cooker is higher than that of box type cooker, however, efficiency with two liter is higher than that of with one liter of volume of water. This is due to the fact that output exergy is directly proportional to the volume of the water.
- Mean exergy efficiency with 250 g of rice for paraboloid type solar cooker is found to be higher than that of box-type cooker. Therefore, in general it is found that exergy efficiency of paraboloid type is greater than box type.

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