Experimental Investigation of Double Exposure Solar Cooker with an Asymmetric Compound Parabolic Concentrator

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Abstract. This work provides the experimental test results and findings of solar cooker developed in Bahirdar. The cooker is double exposure type consisting of plane reflectors being fixed on top glazing and an asymmetric compound parabolic concentrator fixed on the side wall. It has a box casing with an aspect ratio of 2.66 and overall dimension of 920 mm × 343 mm × 400 mm. Stagnation tests were conducted on the double exposure and conventional solar box cooker. From the test maximum absorber plate temperature of 145 °C for the double exposure and 122 °C for the conventional cooker have been achieved at 12: 30 PM and 12:40 PM respectively. The respective first figure of merit values were found to be 0.123 and 0.088, the former satisfying minimum requirement as per BIS. Water or load test conducted indicates as it has taken 2 h and 30 min for 2 L of water to boil in the double exposure solar cooker while in conventional cooker water doesn't reach its boiling point, being heated to a maximum temperature of 88 °C. For the food cooking, 1 kg of rice distributed in two pots was cooked in 1 h and 35 min, starting from 10:00 AM. 1 kg of bean was cooked in 2 h and 45 min. The double exposure cooker is therefore able to cook hard meals like bean and soft meals like rice and spaghetti two and four times per day respectively. This food cooking result has good implication that if intensive work is done, solar cookers can be disseminated into and used by the society.

Keywords: Double exposure solar cooker · Conventional solar cooker · Vertical glass cover · Food cooking test

1 Introduction

One of the world's great concerns today is energy. Whatever its forms and its source, it is needed by every society and sector or organization in the world for different applications. Cooking is the prime activity made by every society, that needs a great percentage of energy needs of the world. In developing countries biomass, specifically firewood, is the major energy source for cooking. Even though it is considered as a renewable energy source, it has series draw backs. Deforestation leading to famine and draught, air pollution due to fire wood burning, health problems and risk of kitchen burning due to fire wood cooking are some of the problems facing this energy sector. This makes the research community to focus attention on the free, abundant and clean energy source: solar energy! This can be harnessed by devices for different energy

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needing applications. Solar cooking is the most viable, simplest and direct application of solar energy [1, 2].

Solar cooker is a device which utilizes solar energy to cook food, and enable processes like pasteurization and sterilization. The focus of this work is on solar box cookers due to its ease of manufacturing and lower attendance for manual tracking. Researches on solar cooking from the first solar box cooker till now played a vital role for solar cookers to be efficient, cost effective and socially viable. The developments include material type, size and orientation of the cooker as a whole or components: absorber plate, reflector, cooking vessel, glass cover and insulation [1, 3]. The literatures reviewed here after are to catch up the modifications in researches on size and orientation of components.

S. Mahavar et al. [4–6] have designed and tested a solar box cooker for a single family, by making the cooker very light weight, increasing the performance and to have a relatively low cost. They also determined the optimum load range for the solar cooker at which the total cooking time together with other cooker performance parameters would be better to be 1.2–1.6 kg. F. Yettou et al. [7] have compared the performances of two box type solar cookers having horizontal and inclined aperture apertures. The cooker with inclined aperture was observed to have better performance than horizontal one due to increase of absorption area. Sethi et al. [8] also have designed and developed an inclined solar box cooker with one reflector. Tests were conducted on this developed cooker and compared the results with the horizontal cooker having similar dimension and material, showing that the former has a better performance.

Reflectors in solar technologies are used to increase the amount of solar radiation intensity falling on the absorber surface. The increase in number of reflectors increases the performance. Zied Guidar et al. [9] have designed and constructed a box cooker with four outer reflectors. Test conducted and performance calculated reveals as the first figure of merit is 0.14, which is greater value compared to the cooker without reflector. Absorber plate temperature was 133 °C which is better than the later. Amanuel Weldu et al. [10] designed and experimentally investigated a box type solar cooker with single reflector that can be optimally tracked every hour. The test results show that, the performance is better than cooker with fixed reflectors, which in turn is better than solar cookers without reflectors. But the boiling time is not less than 3 h for the optimally tracked one, which should be enhanced.

The common problem for many box type cookers is their need for frequent tracking in order to capture sunlight effectively in sunshine hours. There are many scholars who did to improve the tracking and make it to be performed little times per day, per month or per week or make it non tracking. Mirdha et al. [11] have tried a variety of combination of reflectors to have high value of collection coefficient for reflectors and reduced adjustment periods. The final cooker developed has fixed vertical wall reflector facing to south along with another south facing reflector on its lid which is trackable. It had side mirrors to remove permanent movement of the cooker throughout the day in the direction of the sun, as it goes from east to west. Harmim et al. [12] have developed and tested a solar box cooker having ACPC fixed on vertical side wall of the cooker. The cooker itself is fixed on the wall of south facing building, so that indoor cooking is being made, which is socially viable.

Solar cookers were also designed to increase solar absorption by exposing the absorber plate for solar radiation from different directions, albeit it was receiving solar energy from above horizontal glazing in earlier times. Saravanan and Janarathanan [13] have developed a double exposure cooker and compared its performance with the conventional cooker exposed only from above. This cooker is so huge in size requiring wider location area more than a simple kitchen house. In addition, arranging the side reflectors to keep timely movement of sun is also a difficult task. Increasing the number of reflectors increases the performance of the cooker. In addition, tracking the reflectors based on movement of sun, also increases the performance [9]. Scholars also have noticed that outer reflectors fixed on the box cookers have a drawback, as tracking of reflectors needs continuous attending and also the reflector by itself increases size of the cooker. Mulu Bayray et al. [14] have designed a box cooker with internal reflectors, whose performance have been better than solar cookers without reflectors. But still such cookers have low performance, taking long cooking hours. Solar cookers were also developed with non-tracking concentrators aimed both at increasing performance and cooking to be made unattended [15].

In spite of such efforts being made on solar box cookers, they are not widely used. Specifically, in Ethiopia, the technology is unknown by the society. Great effort is expected from scholars to make it socially viable, efficient and disseminate towards the society. Most of highly populated countries including Ethiopia are blessed with high solar radiation in the range of 5–7 KWh/m^2 and have shiny days on average of 275 days per year. Therefore, it can easily be said that solar cookers in Ethiopia have higher potential on being a supplement for energy demand of cooking if efforts are made for cases mentioned before [16].

Even though efforts are made to reduce the cooking time, they are not compatible with the rural society. For instance, solar box cookers with tracking plane reflectors have been seen to be tracked every hour, day or in the interval of some specified time. Double exposure solar cookers discussed so far requires very wide space [13]. Some also have a series of flat plates, fixed on parabolic path from below of box cooker. These flat plates are tracked continuously throughout the day following solar path, and this is difficult to operate for the illiterate rural society (the case for Ethiopia). Even though it is possible to operate, standing outside for follow up at sunny day is the other side effect. It was seen in literatures, there have been works to develop solar cookers with non-tracking reflectors. But their performance is lower than other box cookers [17, 18].

In this work it is intended to develop double exposure solar cooker that does not require frequent tracking and perform as good as trackable plane reflectors. This is made by adding asymmetric compound parabolic concentrator to the vertical side of the box casing, on conventional solar box cookers which have plane reflectors.

Compound parabolic concentrator is a non-imaging concentrator that is used for concentrating all solar radiation falling on it to the receiver at a wider limit called acceptance angle. It has been used for high temperature application that does not require frequent tracking, once it is installed in appropriate direction. When the parabolic concentrators are asymmetric, it can be integrated with vertical walls of a box and buildings for facade integration. These have been normally used for indoor cooking and photovoltaic generation with building integration [12, 19–21].

2 Materials and Methods

2.1 Design and Description of the Developed Solar Cooker

The box casing dimensions was determined by considering the amount of energy it would intercept by absorber from the reflector. In doing so, the amount of energy required to cook a specified food is determined and then used to size box dimensions.

2.1.1 Cooking Load

Rice is to be cooked as a sample once for a family and the ratio of water needed for the specified amount of rice is taken from literature. For the 0.5 kg of rice, which is the average consumption for a family the amount of water needed is 1.25 L [22].

In cooking, there is a specific range of load that is optimum in terms of cooking time, and other performance parameters like thermal efficiency, figures of merit. For a family cooker the optimum amount of load to be cooked was determined to be 1.2–1.6 kg [11]. Hence, the water amount calculated for the family cooking is in the optimum load range.

The energy required at the cooking pot which is to be determined is equal to the sensible heat load of water and food ingredients in cooking, plus energy needed for maintaining boiling temperature due to loss of energy through evaporation of water during or before boiling temperature. The sensible heat load is calculated from the temperature increment of water from its initial value of ambient temperature to the cooking temperature which can be taken as boiling temperature of water.

To know the full load, the ingredients to be used in the cooking, should be specified. Ingredients used for cooking it are: onion and oil. Compared with the water and rice, the other ingredients are very small in proportion. So, cooking load can be determined from the two with a certain percentage increment.

$$E_s = m_w c_{pw} \Delta T + m_r c_{pr} \Delta T \tag{2.1}$$

The given quantities and physical properties are $m_w = 1.25$ kg, $c_{pw} = 4.22$ kJ/kg.K, $m_r = 500$ g, $c_{pr} = 1.8$ kJ/kg.k and ΔT is temperature difference between the boiling and average ambient temperature of water, which are 94 °C and 21 °C respectively. Substituting these numerical values into the equation, the value of total energy required is 432.525 kJ. It is the total amount of sensible energy required at the cooking pot throughout the cooking period.

It is found from literatures that the amount of energy needed for maintaining cooking temperature can be approximated as one third of sensible heat energy required [23]. The total energy required for cooking is then,

$$E_t = E_s + \frac{1}{3} E_s = 576.7\,\text{KJ} \tag{2.2}$$

This thermal energy is acquired from the incoming solar radiation. In the cooking period, there are many convections, radiation and conduction losses from the pot and other cooker components like glass cover and absorber plate. Hence the calculated energy value is the net energy at cooking pot irrespective of these losses.

2.1.2 Box Casing

This is the parallelepiped shape on which other components are attached and inside which the cooking pot is placed. The height and width of cooker are determined by considering: pot size, insulation, reflectors to be added (as the box should be structurally able to carry plane and parabolic reflectors) provided that absorber plate inside it is able to capture sufficient energy for cooking. Rectangular shaped solar box cookers perform better than square shaped once. The optimum length to width ratio for box type cookers was determined to be 2.66 [24]. Hence length can be calculated using this ratio, once the height and width are determined based on the above considerations.

The box casing can be made from locally available humanitarian waste materials like cardboards and stronger materials like wood, ply wood and steel. Each material has its own merits over the others. The box casing in this study should be structurally able to support the ACPC at its walls and from upper glazing. It would also be good if it has lower thermal conductivity so that it would have insulating property to retain heat. The box material is taken to be plywood due to its higher strength and availability, cheapness and lower thermal conductivity (serving as insulation also).

Since any design problem goes in either of the two methods (determining size and dimensions with given operating parameters and vice versa), in this study the sizes of different parts of the cooker would be determined from the heat load calculated before.

Determination of the size of box casing includes the design of basic components of the cooker like absorber tray, reflector and glazing. This is because the casing is used to hold up all these components together serving as a basic component for the cooker assemblage.

The width of box includes the diameter of cooking pot, sufficient gap for air circulation, insulation. It is possible to simply consider these factors and assign certain numerical value. But it is impossible to know whether this width of box with the length can intercept the desired solar insolation to get the total energy calculated before. Hence, width of box should be calculated based on the energy requirement.

The following assumptions are taken, which are mostly valid for many solar cookers developed so far, for calculation start up and sizing of components.

- The cooker would have an overall efficiency of 30%.
- Cooking would be achieved in 1.5 h (Many recent solar cookers can cook in 1.5–2 h period)

The efficiency and cooking time values are taken based on the following reasons. Many solar box cookers have thermal efficiency in the range of 25–35%. Solar box cookers which are smaller in size have thermal efficiencies around the upper limit of the above range [10, 25]. Solar box cookers having greater sizes have efficiencies around the lower limit of the range given [18]. The solar cooker developed in this work is aimed at achieving cooking without tracking of reflectors. To achieve this, there is a stepped absorber plate: Horizontal absorber plate at bottom of cooker and vertical absorber plate for absorbing solar radiation from ACPC. When doing this, the size of absorber plate and its area increases. Increased in absorber plate area also brings increased heat loss. Hence, the efficiency may not be improved. So, the author picks a numerical value for the cooker efficiency from this range.

The total energy required at the pot is related with solar insolation as

$$\eta = \frac{E_t}{IAt} \tag{2.3}$$

A, is intercept area of the solar cooker which includes effective area of glazing and reflectors, and the numerator is the total energy required which is calculated from the ratio of average solar daily radiation to sunshine hour for the experimental location: Bahir Dar.

$$\begin{aligned} I &= \frac{Average daily solar isolation}{sunshine hours} \\ &= 726\,\mathrm{w/m^2} \end{aligned}$$

The calculated solar irradiance is the average global irradiance on horizontal surface. Substituting these values of variables gives an intercept area to be $A = 0.48\,\mathrm{m}^2$.

In solar collectors, the reflectors have significant effect on the solar energy collection. Researches conducted on the investigation of the effect of reflectors on solar radiation captured have showed as the addition of reflectors can increase radiation capture 1.5–2 times than cookers without reflectors [10, 26]. This increase in collection coefficient is due to the increased aperture area by addition of reflectors. There is no exact mathematical equation that relates the aperture and absorber areas. Hence, this collection coefficient is used for rough estimation of the absorber area from the aperture area calculated in Eq. (2.3).

$$A = 1.5A_{ab} \tag{2.4}$$

Where A_{ab} is absorber area, which is calculated to be 0.32 m^2. This absorber area is the product of its length and width. The optimum length to width ratio for rectangular box cookers is 2.66 [18].

$$A_{ab} = lw = (2.66w)w \tag{2.5}$$

From Eq. 2.5 the width of absorber plate and hence the width of the solar cooker is 0.343 m, and the length is also calculated to be 0.92 m.

The box height should be enough for what was mentioned in the case of width. In addition, the vertical absorber plate which absorbs the solar radiation from asymmetric compound parabolic reflectors should be larger in size, as the aperture should have sufficient gap. It is taken to be 40 cm. Therefore, overall dimension of the box casing is 920 mm $\times$ 343 mm $\times$ 400 mm. The cooker is made of plywood of 20 mm thickness, with openings from two sides for loading and unloading of cooking utensils (Fig. 1).

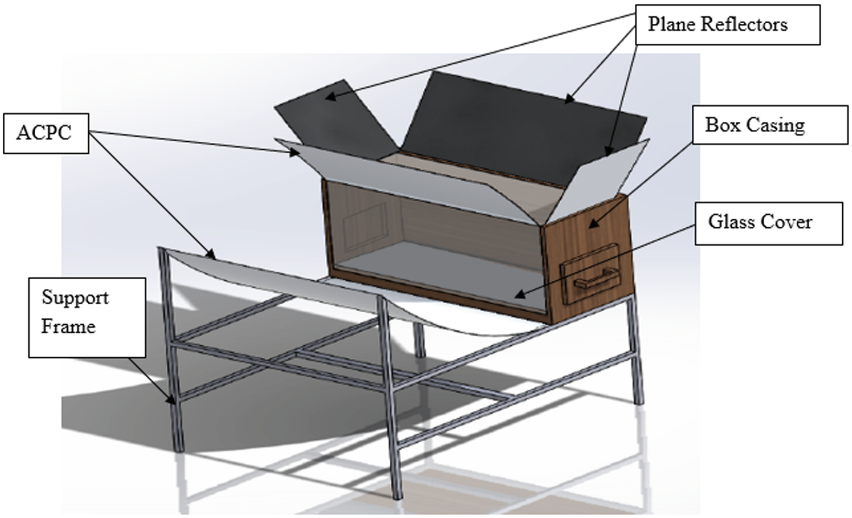

Fig. 1. Developed solar cooker

2.1.3 Glazing

Glazing in a solar technology indicates glasses or plastics used in collector and solar cooker coverings. In solar box cookers it covers the absorber plate allowing sunshine to reach it. It does so for preventing rain, wind, and cold from reaching the plate surface that will cause loss of heat. The transparent cover (glazing) is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector. The glass is transparent to the short-wave radiation received from the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate. Although glass is virtually opaque to the long wave radiation emitted by collector plates, absorption of that radiation causes an increase in the glass temperature and a loss of heat to the surrounding atmosphere. Water white (low iron) glass is better in transmittance than polyester and window glass and it is selected in this work for its good transmittivity [27]. The top and front sides of the box casing in this study are covered with 4 mm thick white glasses, which allows solar absorption from top and front sides that are reflected from the plane and compound parabolic reflectors respectively.

The solar radiation passing into the box casing through the glazing is then absorbed by the absorber plate. It is a metal sheet of high thermal conductivity painted black, for changing the absorbed solar energy into thermal energy.

To reduce the heat loss to the environment, an insulation material of low thermal conductivity is provided between plywood casing and absorber plate. Fiberglass of insulation 40 mm thickness is used [27]. The thickness of this insulation is made to be lower than the recommended value for solar box cookers, as the box casing made of plywood by itself is highly insulating material. The 4 cm fiber glass is to be used at the bottom and rear view of the box. The material of box casing is made with plywood of 2 cm thickness.

2.1.4 Reflector

The reflectors used in this study are of two types. The first one is plane reflectors that reflect solar radiation on the top to horizontal absorber plate. The second reflector is asymmetric compound parabolic reflector that is fixed on the vertical wall of the box. Aluminum foil is used for the reflective material which have good reflectance unless there are many surfaces wrinkling upon it, and it is glued over the steel sheet [27].

The size of plane reflector is determined in a way that the solar radiation striking it should reflect towards the glazing. Even though increasing the size increases the amount of reflected radiation, the shadow effect of higher width reflectors would decrease the performance. Also, solar radiation may reflect from one mirror to the opposite one and again reflected back to the atmosphere. The optimum size for reflectors is taken to be the same size as cooker box width [28].

The specifications of the developed solar cooker are summarized and presented as follows in Table 1.

Table 1. Specifications of the developed solar cooker

SN	Component name	Specification	Material used
1	Box casing	343 mm × 920 mm × 400 mm	Ply wood of thickness 2 cm
2	Absorber plate	343 mm × 920 mm; 400 mm × 920 mm (Stepped absorber plate)	Aluminum metal 0.4 mm thick
3	Glazing	343 mm × 920 mm; 400 mm × 920 mm (Horizontal and vertical	White glass
4	Reflector	Plane reflectors: 2 (343 mm × 920 mm); 2(343 mm × 400 mm) ACPC with concentration ratio of 2.92	Aluminum foil of 0.86 spectacular reflectance
5	Insulation	343 mm × 920 mm; 400 mm × 920 mm; 2(343 mm × 400 mm)	Fiber glass with 4 cm thickness

2.2 Experimental Setup

The experimental work is conducted in Bahr dar Institute of Technology, Ethiopia. The box cooker is fixed with south facing orientation, as asymmetric compound parabolic concentrators on northern hemisphere should face to south [28]. The tests were conducted as per the international standards of solar cooker test procedures [29–31].

Absorber temperature, ambient temperature, temperature of water being heated and solar radiation are recorded every 10 min, so that these properties are used to evaluate performance measuring parameters like first and second figure of merit, cooking power. All experiments were started at 10:00 a.m. and continued until 4:00 p.m.

The performance of the developed DESC was compared with other cookers performances reviewed from literatures. In addition, a test was conducted on the same developed cooker by covering the vertical glazing by insulation material, plywood. This is used as a controlled set up to see the effect of addition of ACPC on the conventional box cooker with plane reflectors.

K type thermocouples were used to measure various component temperatures of the developed cooker (Accuracy of 0.1% reading + 0.7 °C). Simultaneously, solar intensity was measured by TM-207 Solar meter (3 ½ digits display with maximum reading of 2000 W/m^2) (Fig. 2).

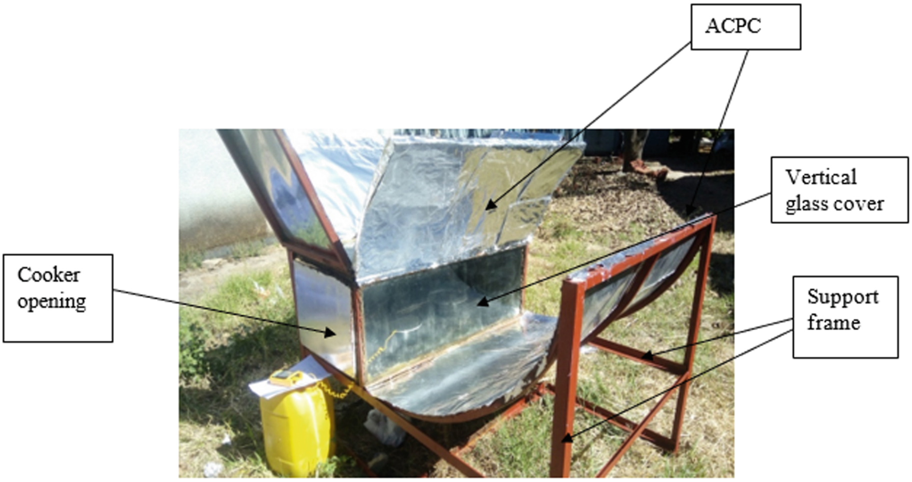

Fig. 2. The manufactured solar cooker on test

Fig. 3. Experimental setup of the box cooker

3 Thermal Performance Parameters

The performance of solar cookers depends on the climatic conditions and design parameters. The climatic conditions which affect the performance of solar cookers are solar insolation, ambient temperature and wind speed. Solar cookers of any type should be tested and their performance should be expressed in terms of some parameters for comparison with cookers designed and tested at different time and places. These parameters of performance evaluation include: first and second figure of merit, standardized cooking power.

3.1 First Figure of Merit

First figure of merit is defined as the ratio of optical efficiency to overall heat loss coefficient. It is the measure of differential temperature gained by plate absorber at a particular level of solar radiation. Stagnation test is conducted to evaluate this parameter in which the solar box cooker is exposed to solar radiation without any load. The mathematical expression is as follows [5–7].

$$F_1 = \frac{\eta_o}{U_L} \tag{3.1}$$

First figure of merit value ensures that the glass covers have good optical transmission and the cooker have lower heat loss coefficient. According to bureau of Indian Standards solar box cookers are grouped into grades A and B. A box cooker with first figure of merit value greater than 0.12 is graded A, whereas cookers having first figure of merit less than 0.12 are graded B [30].

It is determined experimentally as

$$F_1 = \frac{T_{ps} - T_{amb,s}}{I} \tag{3.2}$$

3.2 Second Figure of Merit

Second figure of merit indicates the effectiveness of the heat transfer from the absorber plate and the inside air to contents of the cooking pots. For a box cooker to be said good in heat transfer from vessel to the food contents, the second figure of merit should be greater than 0.4 [30]. It is evaluated under full load conditions and expressed mathematically as Eq. (3.3)

$$F_2 = \frac{F_1(m_w C_w)}{At} \ln\left[\frac{\left\{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_{amb}}{I}\right)\right\}}{\left\{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_{amb}}{I}\right)\right\}}\right] \tag{3.3}$$

Where, I and T_{amb} is average solar insolation and ambient temperature recorded during the test period, for increasing water temperature from a certain initial temperature, T_{w1} *to* T_{w2} in the time interval, t [31]. The upper limit of the water temperature, Tw2 is taken us the boiling or saturation temperature at atmospheric pressure of the environment. However, this has a drawback. Since the rate of variation of water temperature approaches zero as the water temperature approaches saturation temperature, there is a great uncertainty in deciding the termination point of time interval t. Therefore, the upper limit of sensible heating (T_{w2}) should be fixed in the temperature range lower than this temperature by 5 °C–10 °C. Initial temperature, Tw1 could be taken at some value (say, midway) between the ambient and the boiling point [32].

3.3 Cooking Power

Cooking power is the time rate of useful energy gain by the cooker in the cooking or heating period. It is obtained by multiplying the heat capacity of water being heated with the temperature change in the given time interval and dividing the result to the time interval [29].

$$P = \frac{m_w C_w (T_{w2} - T_{w1})}{t} \tag{3.4}$$

This cooking power cannot be directly used for comparing solar cookers at different locations. Hence, it is standardized to the form in Eq. 3.5. The standard cooking power is calculated by correcting cooking power calculated before in to a standard solar radiation of 700 W/m^2. It is calculated by multiplying the interval cooking power by 700 W/m^2 and dividing the result by the average insolation recorded in the interval [29].

$$Ps = \frac{m_w C_w (T_{w2} - T_{w1}) \times 700}{It} \tag{3.5}$$

3.4 Thermal Efficiency

The thermal efficiency of the solar cooker is calculated to know how much is this cooker converting the available solar radiation into useful heat energy that is manifested in the temperature increment of cooking pot contents. Mathematically it is expressed as the ratio of desired output to input energy [10].

$$\eta = \frac{m_w c_{pw} \Delta T}{\alpha \tau \mathrm{IAt}} \tag{3.6}$$

Where α is the absorbance property of the aluminium absorber plate and τ is transmittance of the glass cover whose values are 0.84 and 0.89 respectively [12].

4 Results and Discussion

4.1 Stagnation Test

Stagnation test is experiment conducted when the solar cooker is exposed to solar radiation without any load. This test was made for 4 days (24/12/2018–27/12/2018), 2 for each of the solar cooker types: modified and conventional cooker. The absorber plate temperature and solar intensity variation through out the day is shown graphically in Fig. 3. As seen on the graph the maximum absorber temperature of 145 °C and 122 °C were recorded respectively at 12:30 PM and 12:40 PM respective times, with the stagnation solar intensity of 920 W/m^2 and 917 W/m^2 respectively. Saravanan et al. [13] have designed a double exposure solar cooker and conducted experiment, the test results showing as the stagnation temperature of 102 °C reached after 3 h. Stagnation test results for solar box cookers developed by different scholars reached stagnation

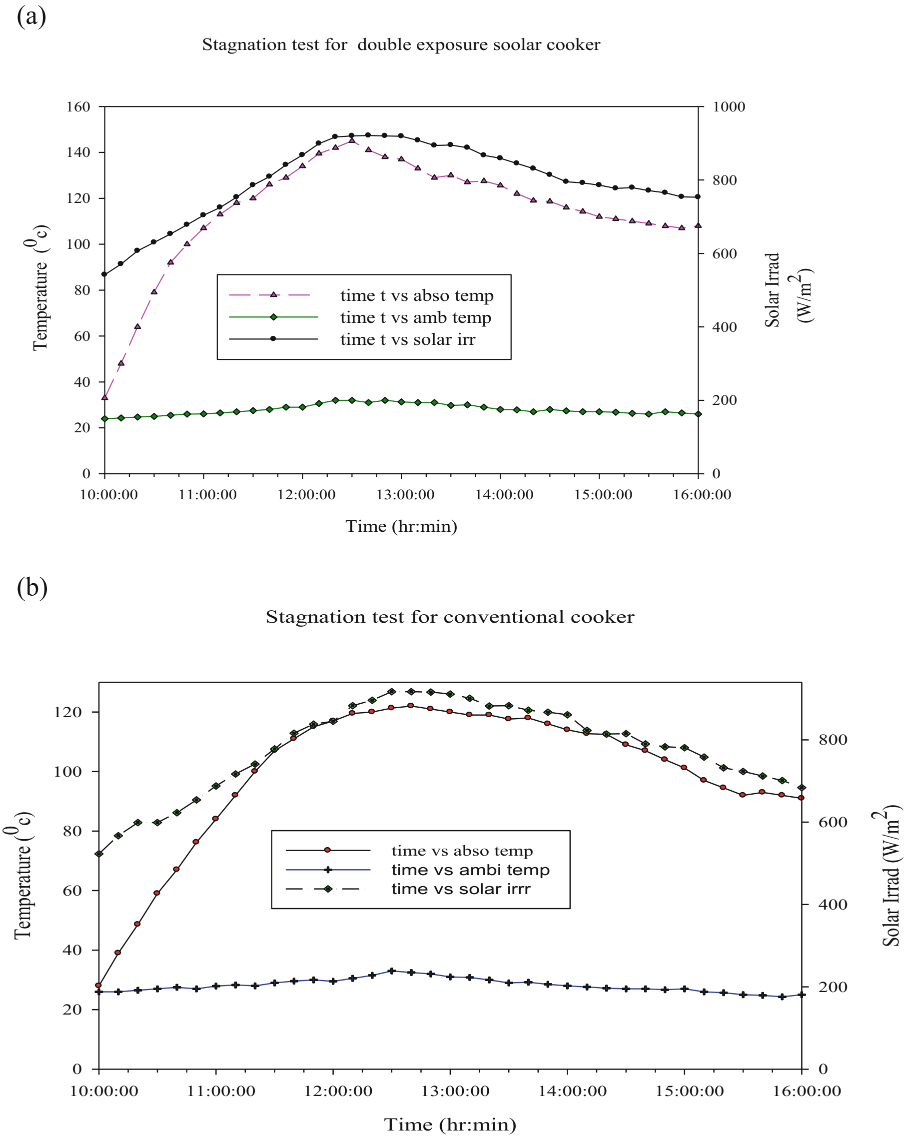

Fig. 4. Thermal performance curve for (a) double exposure cooker and (b) conventional cooker

temperatures of 118 °C, 119 °C, 161 °C [15, 25, 32]. Hence the developed cooker can be categorized as high performing cooker, as absorber plate temperature is one of parameters indicating solar cookers performance [32]. The plot of absorber plate and solar intensity throught the day is shown in Figs. 4 and 5.

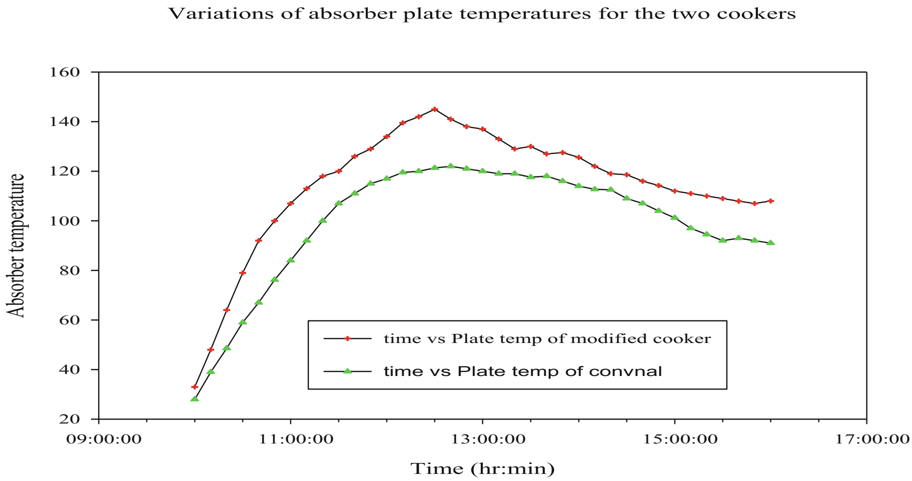

Fig. 5. Variation of absorber plate temperatures for the two cookers

The absorber plate temperature curves in Fig. 4 indicate that, addition of the ACPC on the conventional cooker would increase absorber plate temperature at all times of the test period.

The first figure of merit calculated based on Eq. (3.1) gives, 0.123 for the double exposure cooker and 0.097 for conventional cooker.

The bureau of Indian standards for solar cookers classifies cookers in to major categories by the first figure of merit. Grade A cookers are required to have a minimum value of 0.12 first figure of merit and those cookers having lower figure of merit than 0.12 are classified as Grade B. Therefore, stagnation test results in this work indicate that the modified cooker is Grade A [30].

4.2 Load Test (Water Heating Test)

This test was made with a 2 kg of water load on 2 pots evenly distributed in the cooker (28/12/2018 – 30/12/2018). It is conducted for 3 days, 2 for the modified (graph is done only for one day, as the two days data have almost similar pattern) and one for conventional one.

In this work T_{w2} is taken to be 90 °C as boiling temperature of water in Bahir dar is 94 °C. With these temperature ranges and other parameters known, and the result gives F2 to be 0.41. According to bureau of Indian Standards solar cookers with F2 value greater than 0.4 are taken as good, which this cooker also satisfies [30].

The maximum cooking power calculated based on Eq. (3.6) is 125.1 W and 111.2 W for the modified and conventional cooker respectively, while the minimum value is 16.7 W and 13.9 W respectively. This large value of cooking power indicates greater solar intercept area (and the cooker of coarse is as such), and minimum value indicate poor insulation [29]. The indication of poor insulation is due to increased heat loss through two glass covers, not double glazing, but the vertical and horizontal covers on top and front face.

The variations of temperature values for different components and solar insolation with time are shown graphically in Fig. 6 and 7.

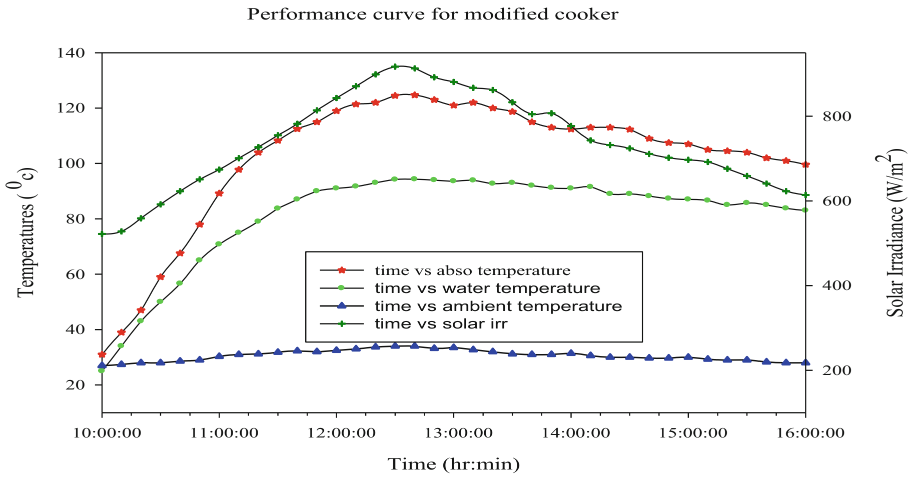

Fig. 6. Thermal performance curve for load test for the double exposure solar cooker.

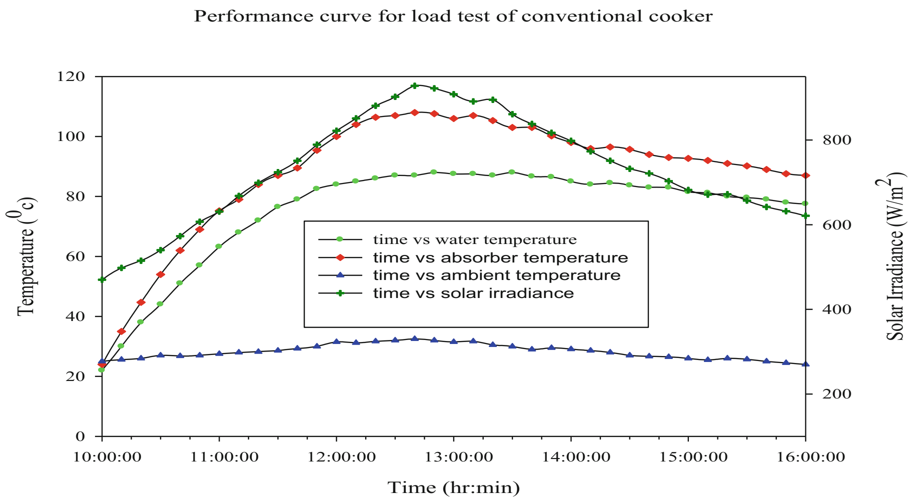

Fig. 7. Thermal performance curve for load test for the conventional cooker.

4.3 Food Cooking Test

In addition to the international test standards and parameters, actual cooking of different food types have also been made. This is why the solar cooker was also developed. Figure 8 shows foods cooked in these cooking days.

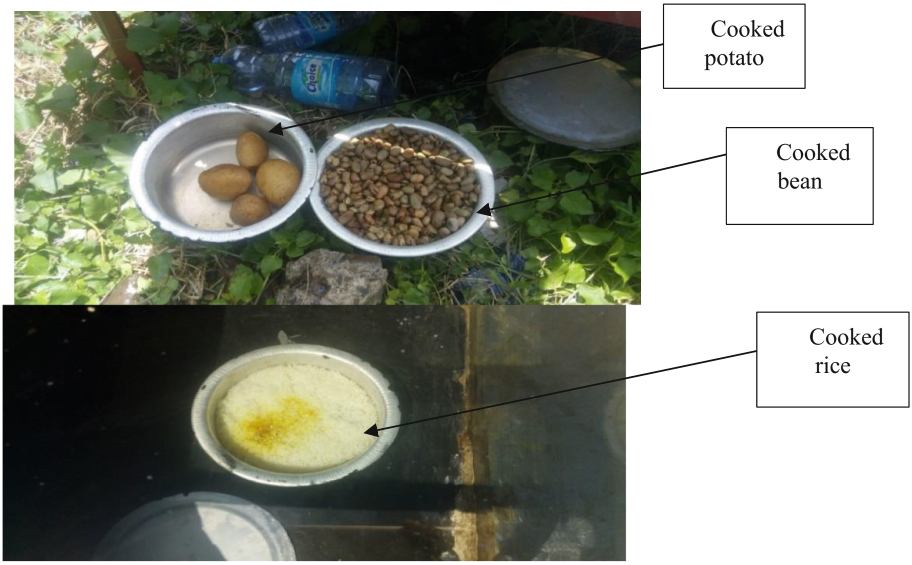

Fig. 8. Foods *Cooked by the developed DESC*.

The test conducted on December 31/2018 and January 1/2019 shows that one kg of rice was cooked in 1 h and 35 min, the cooking starting at 10:00 h. It seems to be contradictory that, water boils after 2 h and 30 min but the rice is cooked in smaller time duration than this boiling time of water. This is because, the cooking was made by adding proportional amount of water and rice together, so that cooking is achieved below boiling temperature of water. It is known that food can be cooked in temperature range of 60–90 °C [18]. 1 kg of bean was cooked in 2 h and 45 min, so that for hard foods it is possible to cook two meals per day.

This is best cooker performance when compared with many of solar box cookers developed till now. The nontracking reflector solar cooker developed by Nahar was able to cook soft and hard foods in 2 and 3 h respectively [15]. Rice cooking also conducted on box cooker with wiper mechanism was cooked in 91 min [25]. Different types of food in double exposure cooker, developed by Amer, were cooked in the ranges of 1 h and 30 min up to 2 h and 45 min [33].

4.4 Thermal Efficiency

Substituting the following numerical values, which was given in test period or calculated before, in to Eq. (3.6).

$m_w = 2\,kg$, $C_w = 4180\,\frac{J}{kgk}$, $t = 9000\,s$, Aperture area A = 0.47 m2, Iavg = 738 W/m2, ΔT = 94–25 = 69 °C.

gives, thermal efficiency of the cooker is 27%. This relatively low efficiency is due to increased heat losses from the glass covers. It is known that increase in glass cover and absorber area also leads to increased loss, even though the net value of energy capture is positive. Although this number is comparatively lower than recent solar box cookers being developed, the actual performance on cooking is so good. Satisfactory cooking ability is due to higher amount of solar energy aperture area, the summation of plane reflector and ACPC apertures.

5 Cost and Affordability

The cost of the developed solar box cooker is shown in Table 2.

Table 2. Cost of the developed cooker

Component/material	Measurement unit	Total size	Total cost (Birr)
Aluminum sheet metal	Area (m^2)	0.743 × 0.92	800
Steel sheet	Area (m^2)	2.5 × 0.92	1200
Aluminium foil	Small Roll	1	100
Plywood	Area (m^2)	2 (0.743 × 0.92)	150
Glass cover	Area (m^2), thickness	0.743 × 0.92	320
Insulation	Area (m^2), thickness (cm)	0.743 × 0.92 × 4	300
Angle iron for support	Length (m)	12 m	800
Glue	Number	1	90
Paint ink	Litre	1	90
Labour cost (one person)	Number of days	2	800
Total cost			4650

This total cost of 4650 Birr, is affordable by most of the rural society. The addition of asymmetric compound concentrator, does not have significant effect on the cost. The cost of the cooker is not comparable with the advantages it would bring in terms of decreasing deforestation and decreasing labor work in searching for wood from abroad.

6 Conclusion and Recommendation

Conclusion

The stagnation and water load tests conducted on the developed solar cooker, indicate that the addition of asymmetric compound solar collector would have significant increment to the performance than the conventional solar box cooker. The food cooking also indicates as it is possible to use this cooker for cooking applications especially those which does not require frequent stirring. The cost of the developed cooker is also affordable.

Recommendation

✓ Research works have to be done on increasing performance of solar cookers with out or with minimum tracking requirement, but with increased collection coefficient for reflectors, that can be easily used by the rural society.

✓ Increase in absorber area, also leads to increased heat loss. Researches in these areas should focus on optimizing geometry of the cooker for decreasing heat loss.

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