Development and Performance Evaluation of a Solar Baking Oven

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Abstract. The majorities of rural people in Ethiopia have low access to electricity and depend almost completely on biomass fuels traditionally. Traditional and inefficient burning of biomass fuels for cooking has an adverse effect on both human health and the global climate. Solar energy could be an alternative even though it cannot replace biomass completely. This work has focused on developing a solar baking oven and aimed to shorten the long cooking time in existing box type solar cookers by employing additional parabolic reflecting element under the box to gain additional heat input. The solar oven is designed for a baking purpose since most Ethiopian cultural foods require continuous whisking or stir during cooking which is not comfortable with solar cookers. The maximum absorber pipe temperature is found to be 121.1 °C and the first figure of merit (F_1) is calculated to be 0.1204. The baking test was done to evaluate the baker actual performance and the quality of the bread by placing row bread in the baking tray inside the absorber rectangular pipe. The performances of the baker demonstrated that these devices can play a role in combating domestic energy problem, mainly in rural areas.

Keywords: Solar baker · Box type solar cookers · Thermal performance · First figure of merit

1 Introduction

The majority of households in Ethiopia use traditional biomass for cooking due to the lack of alternative energy sources. The majority of the population cooks their food on an open fire inside or outside of their homes by burning different forms of biomass. A large amount of particulate matters and combustion products emitted from the traditional burning of each biomass fuels have an adverse effect on human health, global climate and local ecosystems in general. It is also highlighted by the World Health Organization that 1.6 million deaths per year are caused by unfavorable indoor air pollution [1]. Excessive dependence on biomass energy also minimizes agricultural productivity by diverting crop residues and animal wastes from farms for energy needs [2]. Similarly, wood scarcities have become more critical; to obtain wood fuel, rural households who depend on collective free wood have to travel further distances, this also causes loss of human availability

N. G. Habtu et al. (Eds.): ICAST 2019, LNICST 308, pp. 610–622, 2020.
https://doi.org/10.1007/978-3-030-43690-2_46

for productive work. Furthermore, wood fuel depletion leads to deforestation and degradation. Three-stone fire is free and quite easy to construct. Due to the simplicity and availability, three-stone fires have continued to be used for cooking in rural communities and wood fuel is being consumed at an unsustainable rate [3–5] (Fig. 1).

Fig. 1. Traditional three stone baking system in Ethiopia [18].

Solar energy could be an alternative even though it cannot replace biomass completely. Ethiopia is a country with all months of sunshine, and it can be converted into heat. A solar cooker is a device that cooks food using solar energy without consuming fuels and the early effort of using solar energy for cooking food was published in 1767, the effort has continued till today to improve the performance of different types of solar cookers [19]. There are different types of solar cookers. Box type solar cooker is quite simple to construct and cheap relative to concentrated type and indirect type solar cookers, but it requires longer cooking time compared to traditional cookers or concentrating type of solar cookers. Thus, researchers have been working to improve the performance

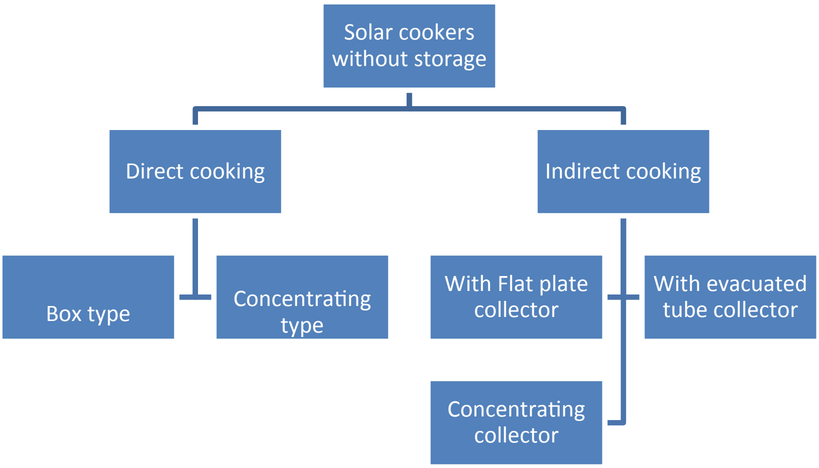


Fig. 2. Classification of solar cookers [17]

of box type cooker to achieve higher temperature and make them more suitable for different cooking traditions. In box type solar cooker the box is insulated at the side and glazed at the top to retain the heat. The booster mirrors or reflectors reflect the solar radiation into the box. Parabolic solar cooker is a concentrating type cooker and it can reach a much higher cooking temperature compared to box type cookers. Concentrating cookers focus a beam of solar radiation on the focus of the collector where the cooking pot is sited. Parabolic solar cookers require tracking of solar during the day in order to give the required cooking temperature [20] (Figs. 2 and 3).

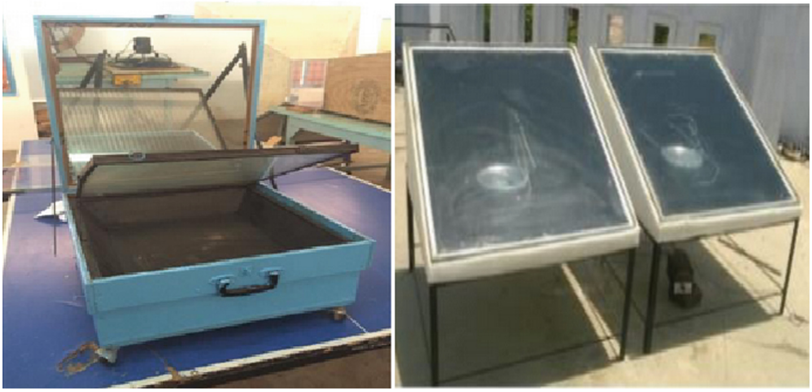


Fig. 3. Conventional box type solar cooker [22, 23].

Many investigations have been conducted in order to improve the performance of the solar cooker and make them more suitable for users. Saitoh and El-Ghetany [6] investigated a solar water sterilization system theoretically and experimentally with thermally controlled flow. Amer [7] examined a novel design of solar cooker theoretically and experimentally in which the absorber is exposed to solar radiation from both the top and the bottom sides. El-Sebaii and Aboul-Enein [8] presented a work to determine the overall heat transfer coefficients between the components of a solar box cooker. Ozkaymak [9] modeled the performance of a box solar cooker. Asfafaw Haileselassie et al. [21] introduced new technology that enables Injera (the most popular food in Ethiopia) baking using a parabolic dish with an aperture area of 2.54 m^2. Adewole [25] evaluated a box solar cooker and he found the maximum plate temperature of 76 °C and first figure of merit is found to be 0.06. Sonali et al. [23] evaluated a box solar cooker with fins and he found the maximum plate temperature of 100 °C and first figure of merit is found to be 0.106. More authors investigated and evaluated different types of solar cookers [10–15].

Even if so many investigations conducted to improve box type solar cookers, the time required for cooking is quite long compared to traditional biomass stoves and concentrating solar cookers. Parabolic collector's cooking times are similar to a traditional stove but require periodic adjustment to refocus it as the sun moves or a mechanical solar tracking apparatus which is more expensive than panel and box cookers. A solar box cooker is cheap and doesn't require expensive tracking mechanism but a major limitation is the long cooking or baking time. The low efficiency and long cooking time in existing box type solar cooker can be improved by combining the principle of a solar box type cooker with a parabolic trough collector. The heating time for a solar box is shortened as the temperature is increased by applying additional parabolic reflection element employed under the box to gain additional heat input. A metal rectangular baking tray is positioned in its focal line. The need for alignment perpendicularly towards the sun is still there but does not require as frequent as it is with a classic parabolic solar cooker. By designing the cooker as a combination of the two, the limitation of a box cooker is dealt, and the work has focused on developing a solar baking oven for break baking purpose since most Ethiopian cultural foods require continuous whisking or stir during cooking which is not comfortable with solar cookers.

2 Methodology

2.1 Product Design Specification

In designing the solar oven, appropriate parameters should be considered, since it is highly considered as a consumer-specific device. The product design specification is based on the knowledge that was concluded in the field study, literature review and theoretical calculations to make sure the design meets the requirements of the users. If the oven is to be the source of income for a person, the output capacity must be large enough to make a sufficient profit. The number of times a person can bake is a variable to the function of bread/day. This number is calculated by dividing the total sun hours per day with the time that it takes to bake. The size of the bread that is to be baked is dependent on what type of bread it is. Even though it is possible to make smaller variants of a specific kind of bread it is important that the oven can bake a locally available size type of bread. To be able to bake good quality bread it is important to have the required temperature. The weight of the oven is considered because the user must be able to keep the oven perpendicular towards the sun as well as be able to transport. In order to be used by everyone, it is important that the oven is easy to use. Safety is also mandatory which describes specifications for stability, not causing burns and safety against theft. The solar baker is constructed from different materials and a number of criteria were considered for the selection of construction materials. Pugh's Method was used to evaluate and to quickly identify the best solution. Based on the decision matrix, Plywood is selected to construct the baker body, aluminum is selected for the parabolic reflector, and booster mirror is selected for the upper reflector.

2.2 Design Description

The solar baking oven is a concept that works by combining the principle of a solar parabolic trough cooker and a solar box cooker. Parabolic trough collector's heating time is shorter because it works by concentrating sunlight into a line which makes it effective but it needs accurate and expensive solar tracking mechanism. The solar box type cooker is less efficient and requires longer heating time but don't require expensive tracking mechanism; the need of alignment perpendicularly towards the sun is still there but does not require as frequent as it is with the typical parabolic solar cooker. The low efficiency and long cooking time in existing box type solar cooker can be aimed to improve by combining a solar box type cooker with a parabolic trough collector. The cooking time is shortened as the temperature is increased by replacing the box interior by parabolic reflection element to gain additional heat input. The baking is done in a focal line and the way of accessing the food is only through the sides where safety precautions have been taken (Figs. 4, 5, 6 and Table 1).

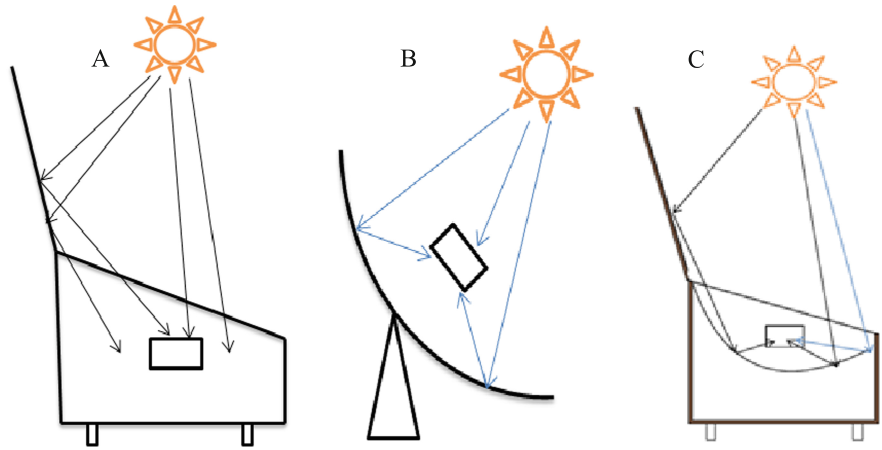


Fig. 4. View of realized concept of box type solar cooker (a), parabolic trough solar collector (b) and the combined solar baking oven (c).

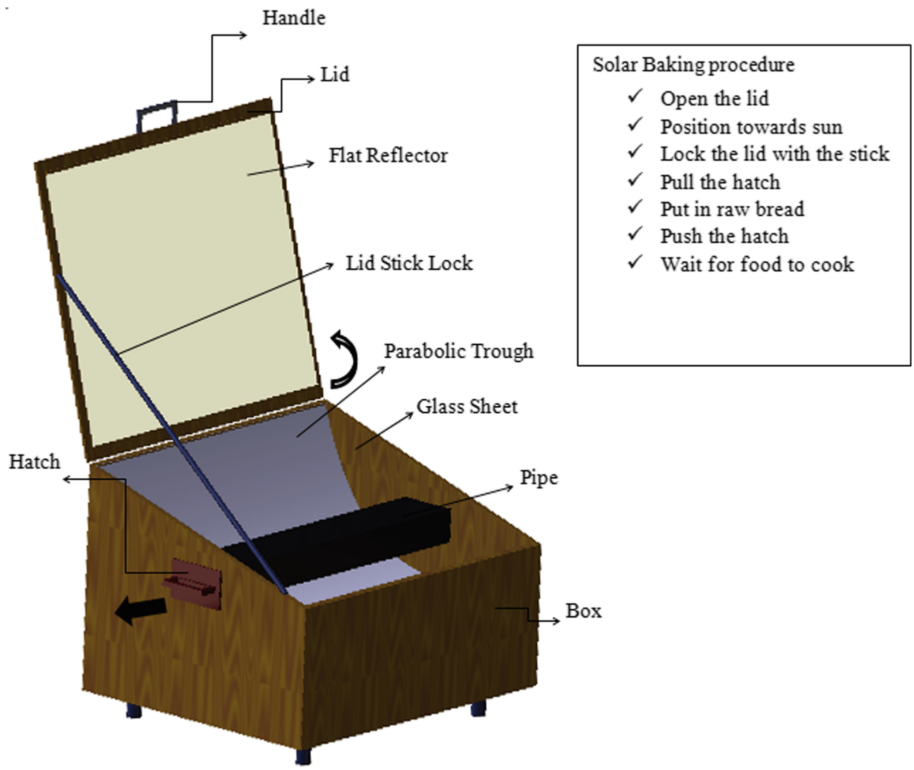


Fig. 5. Final model of the solar baking oven

Fig. 6. Constructed Prototype of the solar baking oven (length is reduced for test only)

Table 1. Product specifications for the solar baking oven.

S/N	Design parameters	Specifications
A.	Capacity	
	1. Breads/day	60
	2. Use/day	4
	3. Number of breads/use	15
	4. Maximum bread size	11 × 10 × 8 cm
B.	Box dimension	
	1. Height (shorter, longer)	250 mm, 400 mm
	2. Width, Length, Thickness	500 mm, 1200 mm, 10 mm
	Box material	Plywood
C.	Glazing glass	
	1. Number	1
	2. Thickness	3 mm
	3. Transmittance	0.9 mm
D.	Reflector	
	Booster mirror	
	1. Number	1
	2. Material	Mirror
	3. Dimension	1200 × 470 × 2 mm
	Parabolic trough	

(*continued*)

Table 1. (*continued*)

S/N	Design parameters	Specifications
	1. Material	Aluminum (1 mm)
	2. Diameter	500 mm
	3. Depth	150 mm
	4. Focal length	104.17 mm
E.	Absorber pipe	
	1. Material	Aluminum (1 mm)
	2. Coating	Black glossy paint
	3. Absorbance	0.9
	4. Thermal conductivity	204 W/m. °C
	5. Dimension	130 × 90 × 1200 mm
F.	Baking tray	
	Material	Stainless steel

2.3 Experimental Methods

Type "k" thermocouples were attached to the absorber to measure the absorber pipe temperature rise sequentially at a given interval until the stagnation condition was found. The tracking of the cookers was done every thirty minutes. The solar radiation intensity was also measured and recorded at a regular interval using a digital solarimeter. Also, actual baking test was done by placing row bread in the baking tray inside the absorber rectangular pipe. The baking test was done to evaluate the baker actual performance and the quality of the bread. First figure of merit (F_1) was used as a performance criterion as per Indian Standard (IS 13429:2000) to evaluate the performance of the baker and to compare and validate the cooker with related cookers. The first figure of merit (F_1) is defined as the ratio of optical efficiency (η_o) and the overall heat loss coefficient (U_L). The desired higher figure of merit could be achieved when the optical efficiency is higher and the heat loss is lower.

$$F_1 = \frac{\eta_0}{U_L} \tag{1}$$

Experimentally,

$$F_1 = \frac{T_{PS} - Tas}{H_S} \tag{2}$$

Where T_{ps}, T_{as} and H_s are stagnation temperature, average ambient temperature and solar radiation intensity respectively.

Standard stagnation temperature is found from [16]:

$$\mathrm{SST} = \left[\left(\mathrm{T_{stagnation}} - \mathrm{T_{ambient}}\right)\left(850\,\mathrm{W/m^2}\right)\right]/\mathrm{G} \tag{3}$$

3 Result and Discussion

Stagnation temperature and baking tests were performed under Bahir Dar weather conditions in January 2019. Bahir Dar is located in Ethiopia at 11°36′ N latitude and 37°23′ E longitude. The stagnation temperature test was intended to measure the standard stagnation temperature and to evaluate the first figure of merit (F_1) of the solar oven. The tests were started at around 11:00 AM and were stopped at 2:00 PM by placing the baker in the open sun (Fig. 7).

Fig. 7. Experimental set up on the solar oven

The maximum absorber pipe temperature is found to be 121.1 °C, which occurred at around 1:30 PM as shown in Fig. 8. The standard stagnation temperature is found to be 102.3 °C. F_1 is calculated to be 0.1204, and solar cooker with first figure of merit greater than 0.12 is marked as A-Grade solar cooker as per Indian Standard (IS 13429:2000) [15]. The first figure of merit can be improved by minimizing heat losses and leakages to the ambient (Table 2).

Table 2. The test result of ambient temperature, absorber temperature and solar insolation.

Time (hrs)	Ambient Temp. T_a (°C)	Absorber Temp. T_p (°C)	Insolation, I_s (W/m^2)
11:00	25	60	716
11:30	25	71	762
12:00	27	96	759
12:30	27	117	781
1:00	26	120	786
1:30	26	121.1	790
2:00	26	119	784

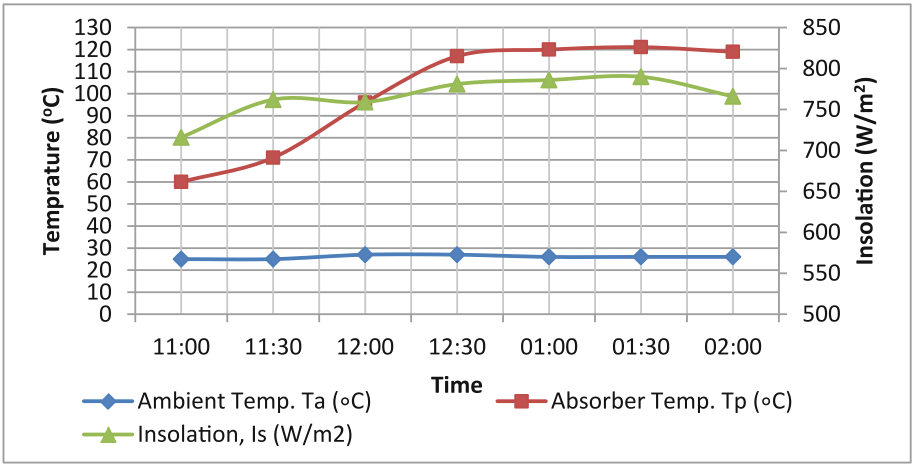


Fig. 8. The rise in temperature of the absorber

Figure 8 shows the temperature rise of the baker, ambient temperature and solar insolation versus time of the day. This experiment monitored the rise in temperature of the absorber plate when no baking has taken place to determine the peak temperature attainable at given solar insolation on a particular time. The pick is measured at noon when maximum insolation is recorded. The peak temperature of the absorber pipe (121.1 °C) is attained at 1:30 PM. The heat up time is shortened unlike most box type solar cookers because of the parabolic reflector inserted inside the box to attain additional heat input. The baking test was done to evaluate the baker actual performance and the quality of the bread by placing row bread in the baking tray inside the absorber rectangular pipe. The baking is done in a focal line and the way of accessing the food is only through the sides. It takes 50 min for the bread to be baked (Fig. 9 and Table 3).

Fig. 9. Bread baked by the constructed solar baker.

Table 3. Comparison of the constricted solar oven with related works.

<table>
<tr><th>Author</th><th>The type of the cooker</th><th>Performance criterion</th></tr>
<tr><td>Adewole [25]</td><td>See Fig. 10

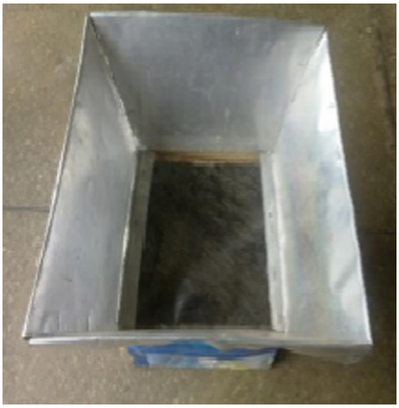



Fig. 10. Reflector based solar box cooker [25]</td><td>$F_1 = 0.08$
$T_{stagnation} = 76\ °C$
Stagnation temperature reached after three hours and twenty minutes</td></tr>
<tr><td>Sonali et al. [23]</td><td>See Fig. 11

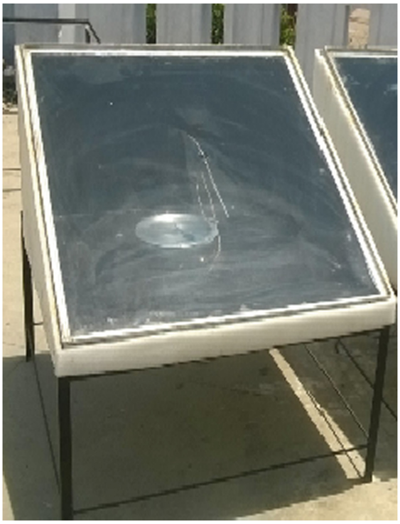
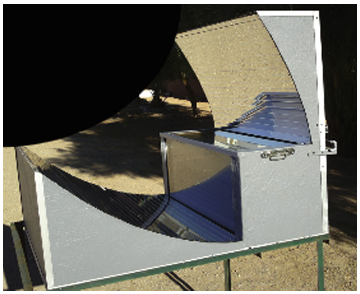



Fig. 11. Typical box type solar cooker [23].</td><td>$F_1 = 0.1061$
$T_{stagnation} = 100\ °C$
Stagnation temperature reached after four hours</td></tr>
</table>

(*continued*)

Table 3. (*continued*)

Author	The type of the cooker	Performance criterion
Saravanan and Janarathanan [26]	See Fig. 12  **Fig. 12.** Double exposure box-type solar cooker [26].	$F_1 = 0.1131$ $T_{stagnation}$ = 102 °C Stagnation temperature reached after three hours
Bisrat and Addisu	See Fig. 13  **Fig. 13.** The constructed solar baking oven	$F_1 = 0.1204$ $T_{stagnation}$ = 121.1 °C or stagnation temperature reached after two and half hour
Harmim et al. [19]	See Fig. 14  **Fig. 14.** Box type solar cooker with parabolic concentrator as booster-reflector [19].	$F_1 = 0.152$ $T_{stagnation}$ = 127.7 °C (in cold season) $T_{stagnation}$ = 165 °C (in hot season) Stagnation temperature reached after three hours

4 Conclusion

The performances of the baker demonstrated that the maximum absorber pipe temperature is found to be 121.1 °C and first figure of merit (F_1) is calculated to be 0.1204. It can be improved by minimizing heat losses and leakages to the surrounding. The heat up time is shortened compared to similar box type solar cookers because of the parabolic reflector employed inside the box to attain additional heat input. Generally, this kind of alternative device can play a major role in combating domestic energy problem especially in the rural areas for baking. Improvement on the baker to attain a higher temperature is recommended for further research work.

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