Research article

Development and performance evaluation of tube-type direct solar oven for baking bread

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ABSTRACT

Solar ovens are not widely used for baking bread. There are some attempts to bake bread using solar energy and obtained a promising result. The aim of this research was to develop and test a tube type direct solar oven that has the potential to be easily fabricated and largely produced at a low cost locally in the developing world. The developed solar oven has an overall dimension of (diameter and length) 0.1 m x 1 m and the height of the parabola is 0.35 m. Simulation of the design to obtain the focal point and bread baking process was done using SOLTRACE and COMSOL softwares, respectively. Both simulation and experiments revealed that almost all the rays fall over the trough. Similarly, COMSOL software showed the baking process which was verified through experimental work. The prototype took 67 min to reach its stagnation temperature of 127 °C, with an F1 of 0.32. Three WBT tests were taken at different days and the result showed that the direct tube solar oven overall thermal efficiency of 43.9%, 42.1% and 38.3% at an average solar isolation of 305 W/m², 259 W/m² and 232 W/m², respectively. The tube type direct solar oven has better efficiency compared to most of the direct type solar cookers. This is due to the air tight cover around the oven which reduces the thermal loss of the oven to ambient air, which is also a cause for the oven's good performance under low solar isolation. Further bread baking test showed that the solar oven has an overall utilization efficiency of 35.0% at an average solar isolation of 396 W/m². The time taken for baking is 16 min longer than its COMSOL analysis. This is due to the difference in design and prototype, especially while producing an air tight cover locally. Addressing this and other performance improvement issues, the solar oven could be disseminated to the wider community especially for people living in the rural parts of the developing world.

1. Introduction

Bread is a dietary item produced by mixing grain flour with water in an oven. The oven could be operated on electricity, gas or other alternative energy sources (Mondal and Datta, 2008). The source of energy for baking especially using petroleum products or biomass creates both greenhouse gases and indoor air pollution. As the world population increases, the need for getting sustainable energy for baking is a must. To change the socio-economic status of peoples living in the developing world, the use of cost effective and sustainable sources of energy is the current and future direction of the energy supply system (Kannan and Vakeesan, 2016).

One of the mechanism of using solar energy for productive-use is the use of solar cookers for cooking or baking application. Solar cooker/oven for cooking/baking application is expected to rise in the coming years due to the possible reduction of greenhouse gases (Cuce and Cuce, 2013). Solar cookers are categorized in a number of ways based on the focus of sunlight on top, sides, bottom of the vessel for cooking or baking applications and indirect solar cookers (Arunachala and Kundapur, 2020). When the sunlight focuses on top and side of the vessel of a solar cooker, they are called either solar box, solar panel or parabolic solar cookers. In the case of a solar box cookers, a number of authors reported that they obtained a promising result (Ashok, 2018; Garg and Adhikari, 1998; Regattieri et al., 2016). Similarly, solar panel cookers were also manufactured and tested by several researchers getting acceptable test results (Ashok, 2018; Bernhard, 1996; Diassana, 2017; Kerr, 1991; Ravindra, 2018). However, few researchers reported a complete picture of the development of solar bread baking with its performance parameters, but there are commercial products used for various application (Mora et al., 2016).
This research focuses on designing, manufacturing and testing of a tube-type direct solar cooker which is affordable and easily manufactured in both household and small commercial applications especially in the developing world. This kind of intervention reduces the dependency of biomass for baking in addition to decreasing the pollution and deforestation. The baking food with solar energy will also have impact on the cost of food as it reduces the cost of energy in the baking process.

2. Material and methods

2.1. Description of the solar oven

The tube type direct solar oven has a cylindrical receiver (oven) made of rolled aluminum sheet that is painted black on the outside. Inside the oven is a sliding tray made of food grade aluminum sheet metal. A high temperature rubber door attached to a sheet metal seals the oven. A transparent air tight square tube made of acrylic plate conceals the oven for insulation. The space between the oven and the cover is sealed with wooden plates at the two ends. And a parabolic reflector made of aluminum sheet metal is used to increase the power output of the solar oven. Additionally, an adjustable stand tilts the oven to the optimum position for high solar heat gain (Figure 1(a) and (b)).

2.2. Design procedure of the solar oven

2.2.1. Design considerations

Small bread in Ethiopia ranges from 50 g to 100 g, but the bread that was considered was 75 g bread based on the widely distributed bread in Addis Ababa, Ethiopia. A bread is considered to be ‘baked’ when its core temperature reaches 92 ℃–95 ℃ (Cauvain and Young, 2007). The crust formation starts at 100 ℃ when moisture content at the surface starts to evaporate. Colorization of the crust (browning of the crust) takes place around 115 ℃ (Cauvain and Young, 2007). Thus, at the end of the baking process the surface temperature of the bread will be close to 120 ℃ (Vanin et al., 2009). For a typical loaf with finished weight of 800 g, there would be a loss of 50–55 g during the baking process which is mostly due to evaporation (Cauvain and Young, 2007). Table 1 shows the input parameters utilized for the design of the solar oven.

2.2.2. Design theory

The energy required for bread baking is the sum of the energy used to raise the temperature of the bread/dough to the required value and energy used to evaporate the moisture content at the surface of the bread/dough (Eq. (1)).

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**Table 1. Input parameters used for the design of the solar oven.**

| No | Item                          | Description                              | Reference/Assumptions |
|----|-------------------------------|------------------------------------------|-----------------------|
| 1  | Location and Latitude         | Addis Ababa, Ethiopia (Lat. 9° 7′ 48″ and Longitude 07° 41′ 8″) |                        |
| 2  | Unit mass of bread            | 75 g                                     |                       |
| 3  | Initial temperature of bread/dough core | 25 ℃                                           |                       |
| 4  | Final temperature of bread/dough core | 95 ℃                                           |                       |
| 5  | Density of bread              | 200 kg/m³                                 | Experimentally obtained|
| 6  | Design capacity of solar oven | 10 loaf of bread per baking session       |                       |
| 7  | Volume of solar oven          | $5.624 \times 10^{-3}$ m³                 | assuming overfilling capacity of two-third |

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**Table 2. Summary of the dimensions of the parabola.**

| No | Item                      | Material                          | Dimension               |
|----|---------------------------|-----------------------------------|-------------------------|
| 1  | Receiver (Oven)           | Aluminum sheet metal painted black | Dia. 0.01 m x 1 m x 1 mm |
| 2  | Transparent tube          | Acrylic plate                      | 140 mm x 140 mm x 4 mm  |
| 3  | Parabolic reflector       | Aluminum sheet metal              | 1.15 m x 1 m x 1 mm     |
| 4  | Front and back seals      | Plywood                            | 140 mm x 140 mm x 20 mm |
| 5  | Oven door                 | High temperature rubber            | Dia. 0.1 m x 13 mm      |
| 6  | Adjustable stand          | RHS (Rectangular Hollow Steel)     | 25 mm x 25 mm x 2 mm    |
The specific heat capacity of bread/dough, $C_p$, varies with temperature according to Eq. (2) (Adamic, 2012).

$$C_p = 0.077T^2 - 68.94T + 16646$$

(2)

$$Q_E = mC_p\Delta T + Q_w$$

(1)

The specific heat capacity of dough/bread, $C_p$, varies with temperature according to Eq. (2) (Adamic, 2012).

$$C_p = 0.077T^2 - 68.94T + 16646$$

(2)

The oven power output depends on the solar radiation collected by the concentrator and reflected to the receiver which includes the overall thermal losses of the oven. The amount of solar radiation that is reflected by the concentrator and absorbed by the receiver can be calculated using Eq. (3) (Duffie and Beckman, 2013).

$$S = \frac{k_0(\gamma \tau a)(\gamma \tau a)}{h_{con}}$$

(3)

Since the transparent tube is square, the equivalent diameter should be determined using Eq. (4).

$$D_e = 1.3(a \times b)^{0.625}(a + b)^{0.25}$$

(4)
The useful energy gain per unit of collector length, $q_u$, expressed in terms of the local receiver temperature, $T_r$, and the absorbed solar radiation per unit of aperture area $S$ is given by Eq. (5).

$$q_u = F_0 A_a L / C_{18} G / C_{0} A_r A_a U L / C_{0} T_f / C_{0} / C_{19}$$

The efficiency of the solar oven can be determined by taking the ratio of the useful heat gain by the dough/bread to the amount of solar radiation collected by the aperture (Eq. (6)).

$$\eta = Q_u / S \times A_a$$

The shape of the parabolic trough reflector can be determined using the following sets of Eqs. (7), (8), (9), and (10) (Macedo-Valencia et al., 2014).

The parabolic equation was calculated using Eq. (11):

$$Y = X^2 / 4f$$

For,

$$0.404 \ m < X < -0.404 \ m \ \text{and} \ 0 < Y < 0.35\ m$$

The final summary of the materials selected and their dimensions are given in Table 2.

### 2.3. Simulation geometry and software

#### 2.3.1. Aperture area and focal point

Using MATLAB code and taking the latent heat of vaporization of water to be 2260 kJ/kg, the energy required to bake 1 kg of bread was 297 kJ. The power to bake this bread in 30 min will be 165 W. Therefore, the tube type direct solar oven is designed based on a minimum requirement of a useful power output of 165 W for a solar isolation of 400 W, which is a minimum solar isolation average of Addis Ababa for 10 months of the year, considering a baking hour from 9:30 AM to 3:30 PM.

Ray tracing simulation of the parabolic shape and thermal analysis simulation of the solar oven receiver were done using COMSOL and Matlab software. SolTrace is a software tool developed at the National Renewable Energy Laboratory (NREL) to model concentrating solar power optical systems and analyze their performance (NREL, 2012).
Thus, by using this software, the focal point calculated and simulated were compared with the ray characteristics at the reflector and receiver. The software takes the following data as its input; latitude of Addis Ababa, day of the year and hour of the day. Aperture geometry and reflector property are also defined in the software based on our selected material and calculated geometry. Figure 2(a) and (b) shows

![Figure 6. Bread baking simulation of the tube type direct solar oven using COMSOL with time: (a) 0 min, (b) 5 min, (c) 10 min, (d) 15 min, (e) 20 min, (f) 25 min, (g) 30 min and (h) 35 min.](image-url)
the geometry and mesh configuration of the bread inside the solar oven.

The parameters used for the COMSOL analysis is showed in Table 3 was used to evaluate the possible temperature distribution during the baking process.

2.4. Testing of the prototype

Tests were conducted from 15 Oct, 2021 up to 25 Oct, 2021 at Addis Ababa Institute of Technology, Addis Ababa University with has a meteorological condition of Latitude 9° 7’ 48” and Longitude 07° 41’ 8”.

The tilt angle for the solar oven was 24° which is the latitude of Addis Ababa plus 15° (Leon et al., 2002). A no-load test, Water Boiling Test (WBT) and bread baking test were conducted to evaluate the performance of the tube type direct solar oven. Figure 3 shows the experimental test set-up of the solar oven.

The instruments used for conducting the test includes a data logger from national instrument (NI DAQ-9211) and thermocouples used to record the water temperature and the oven temperature at different location. A hole was drilled on the oven door and thermocouples were passed through this holes and placed inside the oven. One thermocouple was placed 10 mm above the bottom of the tray using high temperature adhesive tape and the other at the center of the oven. The thermocouples were connected to the data logger and PC. All readings were recorded on the computer using LAB-VIEW software.

2.4.1. No-load test

In the no-load test the stagnation temperature was determined at a solar insolation. In addition, the first degree of merit for the oven was determined using Eq. (12):

$$F_1 = \frac{(T_{ps} - T_{as})}{H_s}$$

where $T_{ps}$, $T_{as}$ and $H_s$ are stagnation plate temperature, average ambient temperature and intensity of solar radiation respectively.

2.4.2. Water boiling test

The water boiling test was conducted on 15 October 2021 during 11:10 a.m. to 11:40 a.m. The standard for evaluation of the performance of solar cookers specify that the test shall be conducted with a load of 7000 g potable water per square meter of intercept area. Thus, the solar oven has an intercept area of 0.1 m², the test was conducted with 700 g of water weighed using an electronic balance [ASAE S580 JAN03]. The WBT is conducted to determine the overall thermal efficiency, $\eta_o$, of the solar oven using Eq. (13),

$$\eta_o = \frac{M_w \cdot C_w \cdot \Delta T}{I_{av} \cdot A_c \cdot \Delta t}$$

where, $\eta_o$ represents overall thermal efficiency of the solar cooker; $M_w$, mass of water (kg); $C_w$, Specific heat of water (J/kg°C); $\Delta T$, temperature difference of water; $A_c$, the aperture area (m²) of the solar oven; $\Delta t$, time required to achieve the final temperature of water; $I_{av}$, the average solar intensity (W/m²) during time interval, $\Delta t$ (Adewole et al., 2015).

2.4.3. Bread baking test

The bread baking test was conducted by placing 1000 g of dough inside the baking tube of the solar oven. During the solar baking process, temperatures of the oven space, bread core temperature and ambient air temperature were recorded in 10 min interval. A bread is considered to be ‘baked’ when its core temperature reaches 92 °C–95 °C (Cauvain and Young, 2007). The bread baking test is conducted to find its utilization efficiency, $\eta$, using Eq. (14).
2.5. Uncertainty analysis

The uncertainty value of the experimental measurements was determined based on Kline and McClintock’s method using Eq. (15) (Das and Akpinar, 2020; Getahun et al., 2021).

\[
U_x = \sqrt{(x_1)^2 + (x_2)^2 + (x_3)^2 + \ldots + (x_n)^2}
\]  
(15)

In this study, the uncertainty analysis of different experimental measurements is shown in Table 4.

3. Result and discussion

The tube-type direct solar oven have been designed, manufactured and tested showing a promising result in terms of baked bread considering the minimum solar radiation in the test location. Figure 4 shows the baking quality of the tube type direct solar oven for different breads.

3.1. Geometry and simulated baking process results

3.1.1. Ray tracing

The ray path is computed from 0 to 1 ns with an interval of 0.01 ns. The results of the ray trajectories are shown in Figure 5.

Figure 5 shows how the solar ray will be reflected on the parabolic trough and reach the receiver for an incidence angle of 0°. All the rays will reach the receiver surface and this validates the design of the solar oven. In practice, this result will be affected due to the presence of surface roughness losses, transparent cover optical losses and some impurities such as dust and foreign particles on the solar oven.

3.1.2. Simulated bread baking process

The COMSOL analysis shows that after 35 min the bread core temperature reaches 95 °C and its crust temperature reaches in the range of
115 °C to 120 °C. Thus, the simulation has a 5 min difference with the analytical analysis. The analysis was taken after the oven is preheated to the required temperature. When oven wall temperature reaches 140 °C. Thus, at time 0, Figure 6a, the bread is inserted in to the oven at a proving temperature of 25 °C. Then after 5 min, Figure 6b, the dough core temperature rises by 10 °C while its outer surface increases by 20 °C. Figures 6c and 6d shows that the bread area which has direct contact with the tray bakes faster than other areas due to conduction heat transfer from the oven through the tray. Thus, from Figure 6e up to Figure 6h the surface temperature of the bread rises at a rate close to 2 K/min and the surface of the bread that is in direct contact with the tray shows a rise close to 3 K/min, while the core temperature shows a rise close to 1 K/min. Therefore, from the resulting temperature displaced, we can identify the time to bake the bread. Even though bread can be baked with different end product properties, we have considered a spongy bread with brown surface. This bread requires a core temperature of 92–95 °C and a surface temperature of 115–120 °C (Cauvain and Young, 2007). Thus, based on our COMSOL analysis the bread will take 35 min to bake. This result shows that our practical baking time for 1 kg of dough using the direct solar oven can be 5 min more than the analytically expected time, which is 30 min.

3.2. Prototype test results

3.2.1. No-load test results

A no-load test, a bread baking test and WBT were conducted to evaluate the performance of the tube type direct solar oven. In the no-load test the oven reached a stagnation temperature of 127 °C in 67 min at a solar isolation of 514 W/m² and at an average ambient temperature of 25 °C (Figure 7).

The average first degree of merit for the oven is, $F_1 = 0.32$. Table 5 indicates the time variations of $F_1$ values with time.

3.2.2. Water boiling test results

Three water boiling tests were taken on Oct 15, Oct 21 and Oct 22, 2021. The average solar isolation during the test was 305 W/m², 259 W/m² and 232 W/m², respectively. The tests were conducted using 700 g of water based on the loading standard of ASAE S580.1 NOV2013 testing and reporting solar cooker performance. The first WBT took 30 min to raise the temperature of water from 24.8 °C to 84.2 °C and the second test took 31 min to raise the temperature of water from 23.8 °C to 74.2 °C, while the third test took 35 min to increase the temperature of water from 29.1 °C to 75.5 °C. The recorded data for the water temperature variation of the three tests with time is shown in Figure 8.

The overall thermal efficiency of the tube type direct solar oven is calculated from the water boiling test using Eq. (13). The thermal efficiency of the first WBT is 43.8 %, whereas the second WBT has an overall thermal efficiency of 42.1 % and the third WBT gives an overall thermal efficiency of 38.3 %.

3.2.3. Bread baking test results

The test showed that for a solar isolation of 396 W/m², the tube type direct solar cooker raised the temperature of bread/dough from 25.1 °C to 88.6 °C in 51 min. Therefore, the total power gained by the bread will be 95.10 W. The power available to the solar cooker is found by multiplying the direct solar isolation, which is 90% of the total solar isolation on a clear day (U.S. Department of Energy, 2021), with the aperture area, 0.808 m², and this gives us a total available power of 272.0 W. Thus, the utilization efficiency of the tube type direct solar cooker for bread baking is 35.0 %. Figures 9, 10, and 11 shows the variation of bread baking temperature with atmospheric conditions for the three testing days.

The tube type direct solar oven was compared to different types of solar cookers based on the above test results. The water boiling test comparison shows that the prototype has a higher thermal efficiency (43.8%), compared to Tolokastsine (38.9%) which is a tube type direct solar cooker without the air tight cover (Mora et al., 2016). In addition, it also has a better thermal efficiency compared with a solar frying for baking injera which has a thermal efficiency of 37% (Hailu et al., 2017). This is due to the air tight cover around the oven which reduces the thermal loss of the oven to ambient air which is also a cause for the oven’s good performance under low solar isolation. Further bread baking test shows that the solar oven has an overall utilization efficiency of 35.0% at an average solar isolation of 396 W/m². The time taken for baking is 16 min longer than its COMSOL analysis. This is due to the difference in design and prototype especially while manufacturing an air tight cover.

3.2.4. Safety and maintenance

In the operation of the solar cooker, it is advisable to wear glasses to protect sun light rays coming to your eyes and create damage. Similarly, the best way to maintain the tube-type solar cooker is to clean thoroughly after every shift of operation of the apparatus.

Figure 10. Variation of bread core and oven space temperature with time for bread baking test of 11 December 2021.
4. Conclusion

There are different types of solar cookers at research level and commercially. Now, the focus here was the development of a tube-type direct solar cooker capable to bake bread. The tube-type solar cooker was designed, manufactured and tested showing a promising result. The average thermal and overall utilization efficiency recorded were 41.4% and 35%, respectively. The solar cooker can easily be manufactured and disseminated for solar abundant areas with reasonable cost. Further studies need to be performed to improve the performance of the solar cooker using different materials. In addition, design for mass manufacturing is an area to be included in future studies.

Declarations

**Author contribution statement**

Yonael Tesfaye Aragaw: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kamil Dino Adem: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed materials and wrote the paper.

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**Data availability statement**

Data will be made available on request.

**Declaration of interest’s statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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