The Optimization of a Commercial-Sized Hybrid Barrel-Panel Solar Oven for Implementation in Tropical Climates

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KEYWORDS. solar oven, tropics, sustainable cooking

BRIEF. The usability and temperature capabilities of a commercial-sized, easily replicable solar oven were improved upon through structural changes, temperature testing, and material comparisons, and cook trials were performed to understand functionality.

ABSTRACT. Three billion people worldwide rely on traditional cooking methods which are harmful to individual and environmental health, and are time and labor intensive. Solar cooking is a promising alternative since this problem is concentrated in areas which receive abundant sun. Designed and built in Phase 1 of this project was a commercial-sized solar oven, conceptualized using rudimentary materials so that it could be easily replicated. Phase 2 focused on improving the oven's temperature capabilities according to observations made in Phase 1. Structural changes were made and two types of each panels and insulation were tested against each other. Temperature testing took place between each change to the oven, and a solar power meter was used to standardize data across weather conditions. In Phase 2, the maximum internal temperature rose from 253 °F to 311 °F, and the finding that neither insulation type nor panel type provided a statistically significant temperature advantage meant that the usable build materials are somewhat flexible. Bread, cookies, rice, and beans were successfully cooked in the oven; food must simply be cooked longer and cook time is dependent on solar energy input. There are plans for the oven to be further improved and sent to Guatemala.

INTRODUCTION.

Globally, three billion people use traditional cooking and heating methods (e.g. coal or woodfire) due to lack of reliable access to electricity [1]. These methods are labor intensive, time consuming, and can be detrimental to an individual's health, and result in an estimated cost of 123 billion USD annually [1-6]. There is tremendous need for a new technology that reduces the necessary labor and time input as well as eliminates the harmful health aspects, but this need is difficult to address due to lack of stable infrastructure and deeply engrained cultural preferences. A promising solution to this problem is the use of solar ovens, since the solar energy they require to function is environmentally friendly, abundant, and free [2, 4, 7, 8]. Solar oven technology uses the sun's energy to heat a cooking chamber, negating the need to use wood or coal [2, 4, 5, 8, 9]. Solar ovens are often considered appropriate for countries located on or near the equator (i.e. the tropics) because they receive stronger and more consistent solar energy needed for optimal solar oven function [9]. Furthermore, many of the people still using traditional cooking methods are concentrated in this area, and therefore, stand to benefit from the implementation of solar oven technology. For example, one country profoundly affected by the detriments of traditional cooking methods is Kenya, where an estimated 75% of people rely on traditional cooking methods [9]. The use of these methods in combination with its equatorial location make it well-suited for solar oven technology. Batchelor *et. al,* determined scores representing the viability of solar oven implementation [3]. Notably, Kenya was given the highest viability score due to factors such as relatively high acceptance of innovation, interest in solar products and cleaner cooking initiatives, history of environmental problems as a result of traditional methods, ideal climate, and diet which complies with the capabilities of solar cooking [3].

Substantial literature already exists on solar ovens [2-21]. There are three main types of solar ovens (box, panel, parabolic) which utilize different formations of reflective surfaces to heat a cooking chamber [2]. No type of solar oven is depicted as superior, as performance was based on varying factors. However, most studies focused on single-family use solar ovens, therefore little information is known regarding commercial-sized solar ovens. In addition, most of the sources which discuss larger-scale solar cooking detail feasibility from a cultural or financial standpoint [13-16], as opposed to a prototyping process which can be found for single-family use ovens [4, 5, 18, 21].

This lack of emphasis on commercial-sized solar ovens is also reflected in industry, with many single-family use ovens available [22], but only one (Villager Sun Oven) commercial-sized solar oven on the market [23]. The Villager Sun Oven advertises temperatures of 500 °F and seven cubic feet of cooking space [23], but costs $10,000 [24]. This price point would be a difficult purchase for populations/schools that rely on traditional cooking methods. Therefore, this study aimed to design and test a commercial-sized solar oven built with widely available materials at a low cost.

Motivation & Objective.

This project started as a collaboration between the Vanderbilt University School of Engineering, Department of Civil and Environmental Engineering, and Christ's Gift Academy in Mbita, Kenya. Christ's Gift Academy expressed interested in a sustainable cooking method that could replace their current traditional cooking methods. To address their needs, a commercial-sized solar oven was developed using rudimentary materials for easy replicability. The design and prototype of the oven were completed during Phase 1. Phase 2 consisted of the optimization and evaluation of variables that influence thermal retention and an investigation into the functionality of cooking with the oven.

Phase 1.

Phase 1 consisted of the design, construction, and testing of the full prototype (Figure 1a). A 55-gallon metal barrel, painted black on the inside, composed the cooking chamber (Figure 1c). A portion of the barrel was removed to allow space for a glass sheet (Figure 1b). A 1" diameter stationary rod around which the oven was rotated to follow the sun in the y-plane intersected the cooking chamber (Figure 1a). A fiberglass water heater blanket insulated the oven. There were eight aluminum sheet panels interconnected to hold each other at an angle of 150° from the glass. The oven sat on a stand made from reclaimed wood, on which it rotated to follow the sun in the x-plane. A door on the side of the barrel allowed for loading of food into the cooking chamber (Figure 1c). Within the cooking chamber, a rack sat on the stationary rod, ensuring food stayed level when the oven was rotated. The oven was covered in marine vinyl for waterproofing, security, and aesthetics. The full prototype reached a maximum internal temperature of 253 °F during Phase 1, and successfully cooked bread. The prototype proved much more cost efficient than its industry counterpart at approximately $450 in terms of material and labor, in contrast to $10,000 [24]. However, improvements to the oven were of interest to increase the temperature capabilities.

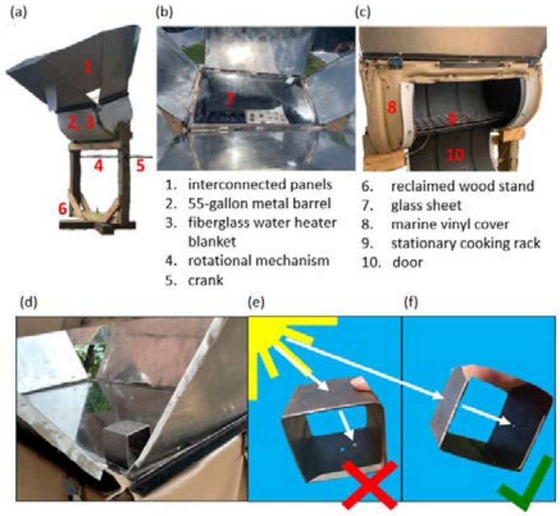

Figure 1. The oven's main design aspects and alignment tutorial. (a) full-size oven model, (b) top view of oven cooking chamber and attached panels, (c) side view of cooking chamber with door open, (d) the solar alignment cube in correct positioning on the oven, (e) the solar alignment cube improperly aligned with the sun, (f) the solar alignment cube properly aligned with the sun.

Phase 2.

The objective of Phase 2 was to optimize the oven according to observations made during Phase 1. This was primarily achieved through improvements to usability and efficiency. Phase 2 also involved standardizing testing methods that varied in the Phase 1 tests, testing in a variety of weather conditions to gain a better understanding of oven performance, and performing additional cooking trials to determine the functionality of the oven with different foods.

MATERIALS AND METHODS.

Usability and Efficiency Improvements.

Improvements to usability were implemented during Phase 2. The panels were interconnected using zip ties. A frame was created to which the panels are attached before they are placed on the oven, and pins are used to attach the frame and encircling panels to the oven. With this, only two people were needed for oven assembly. The interconnected panels flexed out of shape in the wind, so corner supports were added. The stand was also shortened by one foot to allow for the addition of casters that helped increase mobility. Use of casters was unique to the mobility needed for this study and are not required for oven function.

Two factors which hindered the oven's performance were also addressed: the door was closed with cleats using attached nylon rope which can be wrapped around protruding bolts on the barrel of the oven and back on the cleats for optimal closure. Second, a solar alignment cube was created which is placed on the glass of the solar oven and used to rotate the oven to maximize solar energy input (Figure 1d-f).

Materials Testing.

The oven's performance was tested with insulation and panel types to better understand the potential flexibility of construction materials. The fiberglass water heater blanket (r-value = 2/square inch) [25] was tested against mineral wool housing insulation (r-value = 3-4/square inch) [25]. Mineral wool was chosen because of its higher r-value, availability, and low cost. Aluminum panels were polished to increase reflectivity and tested against near-mirror finish mylar.

Temperature Testing.

Temperature tests were performed between 10:30 AM and 4:00 PM CDT. The temperature was taken inside the oven, on the glass, and on two sides of the oven using an OMEGA HH806AU temperature probe or infrared laser thermometer. Solar power in W/m^2 using a TES 1333 Solar Power Meter and ambient temperature were also recorded. Measurements were recorded every 10 minutes. The oven was rotated at roughly 30-minute intervals to optimize solar alignment. Both types of insulation were tested with both types of panels. Statistical analysis was performed using Welch's t-test.

RESULTS & DISCUSSION.

Effect of Usability and Efficiency Improvements.

Addressing the issues associated with door closure and sun tracking proved quite beneficial to the oven's performance. The maximum internal temperature reached in Phase 1 was 253 °F (Figure 2a), while the internal temperature reached immediately after these improvements was 306 °F (Figure 2b). The weather conditions were sufficiently similar to make a comparison between these two days. Thus, this 50 °F increase in maximum temperature can be attributed to the improved door closure and to the use of the solar alignment cube.

Importance and Influence of Solar Energy.

Solar energy directly affected the oven's performance. In Nashville, TN, solar energy readings ranged from 100-1,100 W/m^2 during the late spring and summer months, with higher values indicating stronger sun and lower values indicating cloud cover. Partly cloudy weather resulted in extreme fluctuation of solar energy. There was a correlation between the fluctuation in solar energy and the oven's fluctuations in temperature, with inconsistent solar energy coinciding with temperature declines inside the oven (Figure 2c). In contrast, on a mostly cloudless day, the solar energy input remained much more constant, which was reflected in the oven's much smoother growth in temperature (Figure 2d). Considering that for the trials in Figure 2c and 2d, the progression to 250 °F looked relatively similar, it is suggested that constant solar energy input was crucial for achieving high temperatures. The ability to maintain a higher temperature required consistent solar energy input and was extremely sensitive to small fluctuations. With these observations, it was reasonable that the oven reached only 270 °F on the partly cloudy day while it maintained temperatures above 290 °F on a cloudless day. However, both trials exceed the USDA recommended temperatures for meat to be considered cooked, with the highest necessary internal temperature being 165 °F. Therefore, meat could likely be cooked in the oven if the temperature could be sufficiently maintained [26]. Full cloud cover is unlikely to result in sufficient temperature increase.

Comparison of Panel and Insulation Types.

Four oven configurations were tested to better understand the influence of insulation type vs. panel type: (insulation x panel) mineral wool x polished, fiberglass x polished, mineral wool x mylar, and fiberglass x mylar. Mineral wool resulted in a higher standardized internal temperature than fiberglass (Figure 3a) but they were found to be statistically equal. (Welch's t-test, $\alpha = 0.05$, $p = 0.158$). It seems that higher r-value indicates a general trend toward better performance. Because the oven saw sufficient temperature increase with each insulation type, there are multiple materials which would be appropriate given that they meet a certain r-value. Mylar panels resulted in a higher standardized internal temperature than polished panels (Figure 3b) but they were found to be statistically equal (Welch's t-test, $\alpha = 0.05$, $p = 0.871$). From a usability perspective, mylar is only a thin flexible sheet and was therefore cannot be used alone as a panel material, whereas the aluminum is rigid and self-

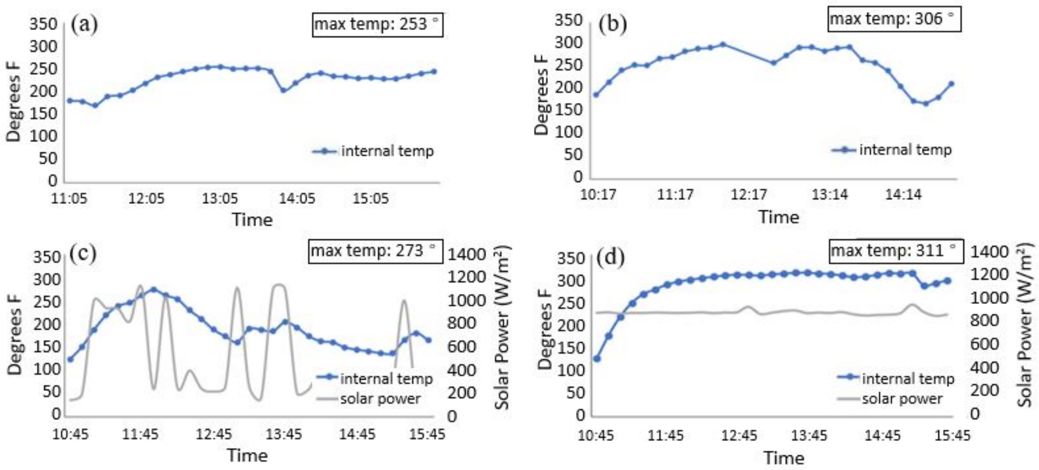

Figure 2. Four of the oven's significant temperature performances. (a) oven's highest internal temperature in Phase 1, (b) the oven's performance immediately following usability and efficiency improvements, (c) oven's internal temperature on a partly cloudy day, (d) oven's internal temperature on a cloudless day, which illustrates the effect of solar energy on the oven temperature growth.

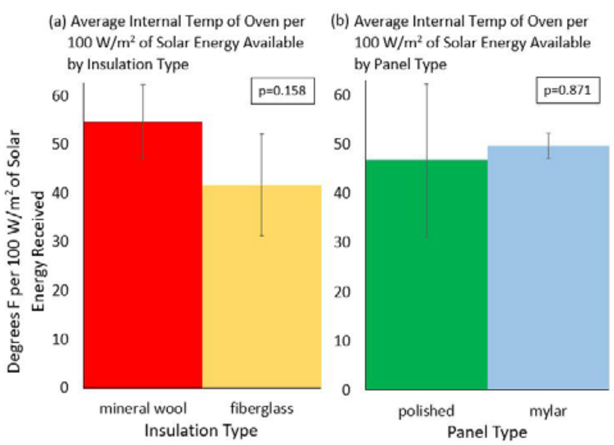

Figure 3. Two types of insulation were tested alongside two types of panels on the oven to determine whether any one material would result in a significantly better temperature output. Temperatures achieved by the oven were standardized according to solar energy input. Average internal temperature of oven in terms of solar energy input by (a) insulation type and (b) panel type.

supportive. It can be assumed that multiple materials would be acceptable for the panels so long as they are sufficiently reflective.

Evaluation of Oven Cooking Functionality.

Bread was cooked in the oven during Phase 1, and cookies, rice, and beans were cooked during Phase 2. Table 1 shows the cooking specifications designated by each food package, the temperature of the oven during cooking, and resultant cook time. The cook time in the solar oven appeared to be proportional to the cook time listed on the package, with the solar cooking time being roughly double that of the food package. The exception was the rice, which likely took a disproportionate amount of time to cook as it was added to the water before the water was brought to temperature in the oven. A similar result was seen in [5, 18]. It should also be noted that the cooking temperatures during all trials were lower than the maximum temperature that the oven is known to reach on a cloudless day. Therefore, a rough estimation of the potential cook time at the oven's highest performance temperature is provided (Table 1). Ultimately, cook time is dependent on solar energy and can vary greatly depending on weather conditions. The findings from these studies featuring

Table 1. Cook Trial Data.

Food	Package Cook Time	Package Temp	Solar Oven Cook Time	Avg. Internal Temp of Oven When Cooked	Estimated Cook Time at Oven's Max Efficiency (311 °F)
Bread (x3 loaves)	25-45 min	350-375 °F	2 hrs	232 °F	1 hr 30 min
Mini Cookies (x16)	9-10 min	350 °F	20 min	234 °F	15 min
Rice (1 lb)	20 min	simmer	2 hrs 45 min	195 °F	1 hr 45 min
Beans (1 lb)	1.5-2 hrs	simmer	4 hrs 10 min	205 °F	2 hrs 45 min

single-family use models would suggest that their results and this larger, commercial-sized oven were comparable.

CONCLUSION.

Internal temperature capabilities rose 60 °F as a result of improved door closure and solar alignment. Neither panel nor insulation type tested had a statistically significant difference, and the oven reached suitable cooking temperatures with all variables, therefore material changes can be made based on cost or availability. Cooking times in the solar oven are likely at least double those necessary for a conventional oven due to lower cooking temperatures. Because this is a passive system, the cooking time depended solely on solar energy input and fluctuated accordingly. The oven's estimated cost of $700 makes it roughly 14 times less expensive than the commercially available alternative. This cost accounts for certain tools available during the construction process that may be more difficult to procure elsewhere and will therefore vary depending on what materials and tools are available. From an analysis of the literature, there are some similar studies [13-17, 19, 20], but none feature the focus on replicability as is emphasized here.

For best understanding of the oven's functionality, it should be tested in a tropical climate. In addition, there are improvements, such as the addition of a second pane of glass (successful in [5]), and steepening of the angle of the panels relative to the surface of the glass to ensure all solar energy is being reflected into the cooking chamber, which could increase the oven's temperature capabilities.

Future Directions.

The opportunity to send the oven to Guatemala is being explored. This prospect stems from a collaboration in which the authors of this study will transition the oven's design to a partner institution. This implementation will allow for a better understanding of how well the oven can be replicated with materials on hand in a given location. The possibility of replicaing the design for use in Kenya is still open.

ACKNOWLEDGMENTS.

Thanks are owed to the CEE Dept, including Dr. Lesa Brown and Rich Teising; my PI Dr. Ralph Bruce; my advisor Dr. Nathan Haag; the SSMV; and classmates Dzifa Dumenyo, Andrew Pelham, and Alyxis Smith.

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