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DEVELOPMENT OF SOLAR BAKING OVEN WITH SENSIBLE HEAT STORAGE

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Abstract: This paper presents the design and development of a solar baking oven with sensible heat storage material which is essentially for baking dough and other confectionaries. Bread is one of the staple foods in sub–Saharan Africa after rice. The increase in the prices of loaves of bread sparked the Arab Spring in Tunisia in 2010. Bread is normally baked in a fossil-fuel-fired oven in most cases. Sometimes, electric ovens are used as well but most of the electricity used to power these ovens is from non–renewable energy sources that pollute the environment. Renewable energy sources are abundant in Sub–Saharan Africa, they are clean and they do not pollute the environment. The baking oven was developed to produce a heating effect without the burning of charcoal, firewood, or other fossil fuels thus reducing the carbon footprint of this activity. Baking using non–renewable fossil fuels has its side effects such as high cost of energy, emission of greenhouse gases, and the possibility of choking by the operator resulting from inhaling of smoke. The system is made up of a solar box oven, solar reflector, heat storage, and insulating materials. Design and sizing of the baking oven and solar reflector are provided. Solar energy incidents on the solar reflector and reflected into the oven cavity through the glass which provides the greenhouse effect in preventing convective heat loss, this then leads to the accumulation of heat in the oven chamber which is used in the baking process. A dough of bread of mass 150 g was baked in 3 hours with the highest temperature of 96.75°C achieved in the oven. The oven was able to retain heat over a long period of time due to granite stones incorporated as sensible heat retention materials.

Keywords: Solar box oven. Reflector. Fossil fuel. Greenhouse effect. Heat storage materials

INTRODUCTION

Sub–Saharan Africa is blessed with renewable energy resources in abundance which include but are not limited to solar energy, biomass, wind energy resources, large hydropower potentials, great potential for hydrogen and hydrogenated fuel, geothermal energies as well as ocean energies. These renewable energies are largely untapped due to a lack of appropriate technology and neglect. The major impediments in the development and penetration of technologies for the exploitation and utilization of renewable energy resources in the region include also, the lack of appropriate policies, regulations, and institutional framework and the lack of the will to stimulate investments in the sector. Electricity generation and penetration in Nigeria is low. Ajao et al, (2011) [1] noted that about 60 percent of Nigeria's population are not served with electricity. Per capita consumption of electricity in Nigeria is approximately 100 kWh as against 1379 kWh, 1934 kWh, and 4500 kWh in China, Brazil, and South Africa, respectively. The Sun's energy is radiated at the rate of 3.8 x 10^{23} kW per second. This energy is propagated radially and reaches the edge of the earth's atmosphere at about 1.5 kW/m^2. The downside of solar energy is that it is not concentrated like fossil fuels but the daily energy received by Nigeria from the Sun is in the range of 5.08 x 10^{12} kWh and with appropriate appliances to harvest the solar energy at an efficiency of just 5 % in an area of about 1 % of Nigeria's surface area, electrical energy in the range of 2.54 x 10^6 MWh can be obtained daily. This electrical energy is the equivalent of 4.66 million barrels of crude oil per day. Some applications of these solar energies can be in drying, cooking, heating, distillation, cooling, refrigeration, and also in electricity generation in thermal power plants (Ajao, et al) [1]. Baking is an essential process as it serves as one of the major food processing and preserving methods. The most commonly utilized method for baking is by firewood and other fossil fuels which are causes of environmental pollution and depletion of forest resources. An oven is a device that is used for baking or cooking as a result of its thermally insulated internal chamber. The first recorded use of an oven dates back to around 29,000 BC in Central Europe. These ovens were made in the form of pits used to cook food such as mammoth meat. From 20,000 BC, Ukrainians used pit ovens with hot coals. The Greeks were credited by culinary historians for developing the art of bread baking after they were able to build front–loaded bread ovens (Ohajianya et al, 2014) [2].

The high concern for the depletion of ozone layer and activities to reduce carbon footprint in human activities led to the invention of this new means of baking which subjects the environment to less or no danger i.e. it brings about a clean environment, this new means of baking uses the renewable solar energy to heat up and bake substances through the reflection of the sunlight on a solar reflector which then transfer heat to the food substance that is contained in the inner chamber of the solar box oven. The need to develop another means of baking that will reduce or eradicate the menace of the present use of fossil fuel in baking is essential. A new type of baking system is developed where solar energy is used as a power source (Hassen, et. al 2011) [3].

The development of a solar baking oven with heat storage material enables the baking of food both during the day and at night without affecting the depletion of the ozone layer as a result of the usage of clean energy in cooking which ultimately prevents the release of harmful emissions into the atmosphere. The basic reason for solar cooking is to heat up food to the required temperature without burning fossil fuel. Solar energy can be used to cook, bake, or fry food items. A solar box can cook because the interior of the box is heated by the sun's radiation through the glass top, direct and reflected sunlight enters the solar box. When the sun's radiation is absorbed by the black absorber plate and cooking pots inside the oven, it is converted into heat energy. As a result of this heat input, the temperature within the solar box cooker rises until the heat loss of the cooker equals the solar heat gain. This phenomenon causes warmth in confined rooms where the sun shines through a clear material like glass. Visible light shines readily through the glass, where it is absorbed and reflected by the materials (aluminum foil) within the enclosed enclosure. The reflected light is either absorbed by other materials in the box or, because it does not change wavelength, it is reflected and travels back out through the glass. The heat absorbed by the black metal absorber plate and pots is transferred via those materials, to bake the food. Heat retention materials can be added to the solar box. The ability of a solar box cooker to store heat improves as the density and weight of the heat retention materials within the insulated box increase. There are basically two types of storage materials which are:

(1) sensible heat energy storage, and
(2) phase change energy storage.

In sensible heat storage, such as rocks, there is an increase in the temperature of the material without the material changing phase. In latent heat storage, the material absorbs heat that is added and goes through a change of phase from solid phase to liquid phase at a certain constant temperature (Saxena and Goel, 2013) [4]. Heat energies are stored in materials that are closely packed which can be rocks, ores, or an enclosed phase change material (PCM), a container, and the transfer of heat through the voids of the bed. There are different ways heat can be transferred to and through the materials. This may be done through convective, conductive, or radiant heat transfer (Sarada et al, 2013) [5].

Many researchers have worked on different types of cookers and ovens that are powered by solar energies [6 – 26]. Some reviews have also been carried out on solar cookers and ovens by many researchers [6 – 10]. Some of these ovens are without any form of heat storage for use when the sun is down [11 – 19] while some are with heat storage devices incorporated in them [20 – 23] and these cookers can still be used after the Sun must have gone down. Domanski, et al (1994) [20] carried out a study to investigate off sunshine hours cooking using phase change materials as storage material in their experiment. They used stearic acid (melting point of 67 – 69 °C) or magnesium nitrate hexahydrate (melting point of 89 °C) as phase change material (PCM). It was discovered that the performance of the cooker was strongly dependent on the intensity of the Sun, the mass of the cooking medium, and the thermo–physical properties of the phase-change materials. Budhi and Sahoo (1995) [21] designed and fabricated a solar cooker with latent heat storage material. They observed that cooking in the evening was feasible by using a solar cooker with latent heat storage. It was observed that the plate temperature was at 57.2 °C during a midnight cooking. Sharma et al (2004) [22] using an evacuated tube solar collector that was equipped with phase change material (PCM) storage, studied the heat performance of a prototype solar cooker. The design comprised two different parts which were energy collection and cooking coupled with a PCM storage unit. The energy from solar is stored in the PCM storage compartment during the time of sunshine and is used for cooking in the evening or at night when the sun is down. They noted that cooking at the noon had no effect on the evening cooking. They also discovered that using PCM heat storage to cook in the evening was faster than cooking at noon. Xie et al (2018) [23] did research on the incorporation of phase change material with the aid of a solar vacuum collector. They obtained a result that shows the effectiveness of PCM usage, which showed that adding phase change material enables the oven's inner temperature to achieve a temperature of 30°C – 80°C higher than the usage of the oven without storage material. The performance of heat storage materials shows that the heat storage layer has a certain heat storage capacity in all seasons and the daily heat storage is about 2718 kJ. Mahfoudi et al (2014) [24] did a simulation on the use of sand as a heat storage material. The setup has a cubic configuration with embedded charging tubes which were used to store solar energy with sand. It was discovered in their results that sand has an important thermal inertia. They observed that the sand bed charging time was about 5 hours and the temperature distribution in the sand bed led to higher energy efficiency of the sand bed. The objective of this work is to develop a solar baking oven with material for heat retention for the purpose of extended use after sundown. This oven aims to prevent pollution of the environment compared to the conventional mode that uses fossil fuel. It is also economical since there is no consumable fuel cost associated with its use and the use cannot be subjected to fluctuation of prices.

MATERIALS & METHODS

Materials

Some of the materials used for the work are given in this section:

— Solar reflector

The reflector, Figure 1, reflects the sun rays into the oven in other to increase heat transfer into the oven. The solar reflector is made of galvanised steel which has two of its sides raised at 67° to one end of it as shown below, a reflective material of 98% reflection is pasted on the inner surface of the structure to enhance reflection. It is used to reflect the light coming from the sun to the baking element which passes through the glass cover on the solar box.

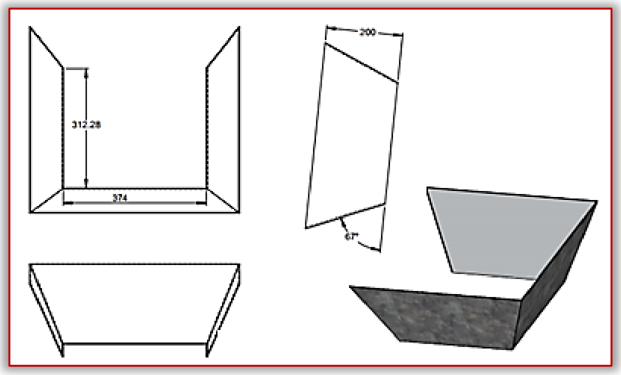

Figure 1a: Design of the solar collector

Figure 1b: 3–side solar reflector

— Solar box oven

The solar box oven is a square-shaped box that is made of three different compartments which are the inner box, the heating storage material compartment (for granite), and an insulating compartment. and the insulating material which is 40 mm thick to prevent heat loss. The entire solar box oven is made of three different boxes, the inner box is of size 250 mm x 250 mm x 150 mm (this is actually the oven cavity). The inner box is the space where the dough is kept for the baking process. It is made of stainless steel in other to enhance proper heating of the food substance and prevent food contamination. The outer shell (casing) of dimensions 400 mm x 340 mm x 150 mm in size, the space between these two casings is where the granite painted black is stored, and the oven is enclosed within another box of dimension 480 mm x 380 mm x 240 mm, the outer cavity is enclosed with fibre glass to minimize convective and conductive heat losses to the environment. Plane glass of 4 mm thickness and dimensions of 400 mm x 340 mm is placed at the top of the oven which allowed inflow of solar insolation and minimized convective heat losses from the cavity.

— Granite

Granite stones, Figure 2, is used as the heat storage material. It is formed and found below the surface of the Earth as a result of volcanic magma eruptions and hardening. The granite used is painted black for good heat absorption and dissipation.

Figure 2: Granite stones painted black

— Glass cover

The glass cover is the medium through which solar insolation passes into the solar box for heat absorption and heating of the cooker and its contents. It also serves as a prevention of the radiant energy from leaving the box cooker thereby creating a process known as the greenhouse effect. This process heats up the oven's inner chamber and the heat storage materials. The glass cover is 3 mm thick.

Experimental setup

After the fabrication of every aspect of the baking oven, the different components were coupled together as shown in Figure 3, and Figure 4. The test was carried out using bread dough to achieve baking.

The temperature of the day was recorded against the time of the day. Thermocouple Temperature Sensor, Figure 5a, MAX 6675 K–Type was used to measure the temperature. The temperature probe was placed inside the oven for the instantaneous temperature readings. Arduino Uno microcontroller board, Figure 5b, was used in this experiment to take the temperature readings of the oven. Jumper wires, Figure 5c were used to connect the thermocouple sensor to the Arduino module.

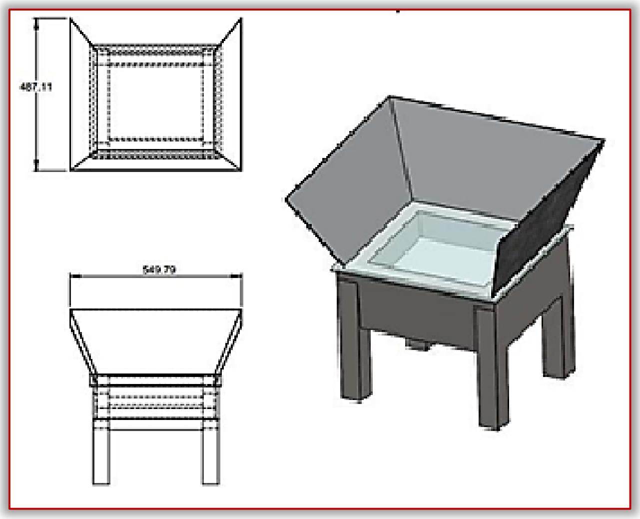

Figure 3. Assembly of the solar box oven

Figure 4: Experimental setup of the solar box cooker

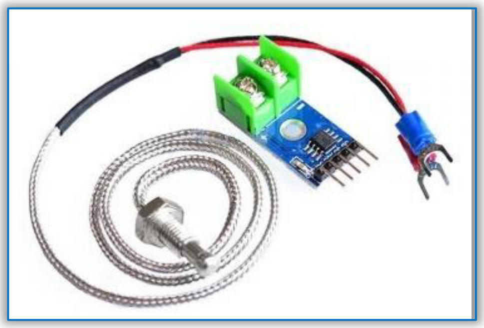

Figure 5a: K–type thermocouple and Max 6675 temperature sensor

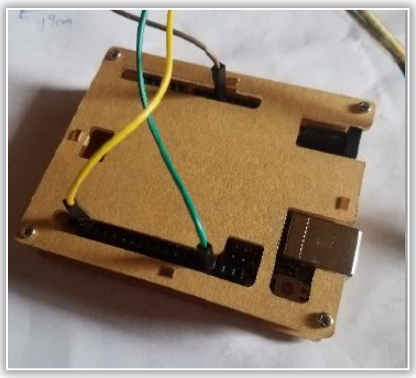

Figure 5b: Arduino Uno module

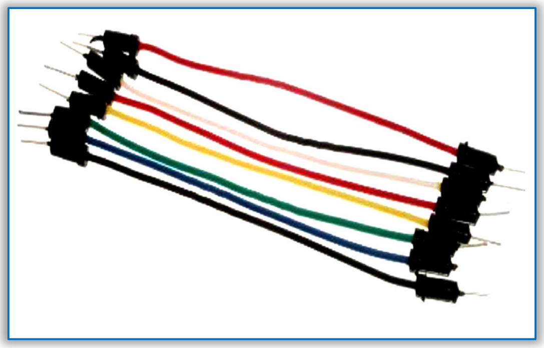

Figure 5c: Jumper wires

Figure 6a is bread dough before baking and Figure 6b is the loaf of bread baked in the oven.

Figure 6a: Dough of bread before baking

Figure 6b: Loaf of bread after baking

RESULTS AND DISCUSSIONS

The solar oven was tested at the Faculty of Engineering, University of Lagos, Lagos Nigeria (6.517985, 3.399527). The temperature obtained during testing was plotted against time in an interval of 15 minutes is shown in Figure 7.

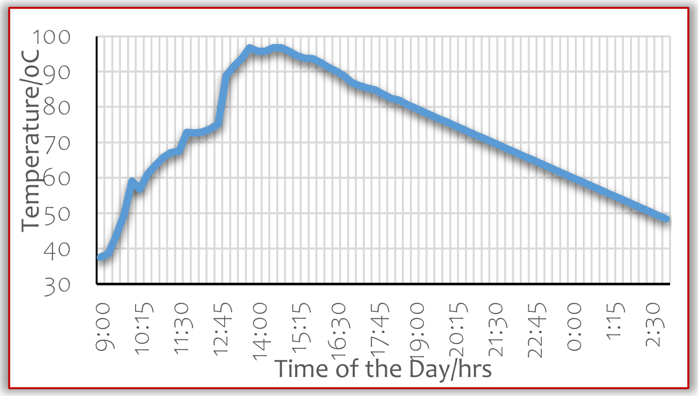

Figure 7: Baking oven Temperature against time of the day

From Figure 7, it was observed that the temperature increased steadily as the sun rose and heated up the chamber and the granites in the chamber. As the sun approached the peak temperature of the day and then the temperature started dropping after the peak temperature was attained. It was also observed from the graph that the oven retained heat for a long period after the sun had gone down which was the purpose of adding heat retention materials. The maximum temperature that was obtained during the day was between the hours of 12:30 pm and 2:30 pm.

CONCLUSION

In this paper, the design and development of a solar baking oven with sensible heat storage material which is purposefully for baking dough and other confectionaries has been presented. It was discovered during the course of the experiment that the time taken to achieve baking is highly dependent on the intensity of the Sun (Solar irradiation). Less intensity of the sun will prolong the time taken to achieve the baking process while the high intensity of the sun will shorten the time taken to achieve the baking process. The heat was retained in the oven for a long time due to the inclusion of heat retention materials and this is also dependent on solar irradiation during the day. This oven can be used even in the rural areas away from power grids. It does not pollute because it uses the energy from the sun which is renewable. The project also incorporates the solar reflector for more effective capture of the Sun energy, which will always aid temperature rise in the oven and fast-track the baking process.

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ISSN: 2067-3809