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Design and Implementation of a Solar Powered Electric Cooker

Ogbekhiulu A. J.[1,*], Rudolf O. A.[2]

[1,2] Department of Electrical and Electronic Engineering, College of Engineering and Technology, Federal University of Petroleum Resources, Effurun.

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ABSTRACT

This paper presents the design and implementation of a solar powered electric cooker which seeks to address and provide a lasting solution to deforestation due to cutting of trees for cooking purposes, and therefore, reduce the amount of CO2 emissions into the environment of a developing country such as Nigeria. The solar powered electric cooker was designed and implemented using the heating chamber, the battery, the charge controller, and solar panel with its stand. The cooking chambers together with the battery and charge controller are coupled together. A 5mm heat resistance coated glass is placed on top of the cooking chambers, so that the heat does not get direct contact with the user and immediate environment. Whenever the switch connected to the system is switched in its ON position, the heated element gradually gets heated up and is set for usage. The charge controller has an inbuilt mechanism that helps to monitor the battery level and whenever the level drains below 10VDC it cuts off the battery from the system to avoid further drains. Performance evaluation was carried out using digital thermometer and 1 kg of water. The result obtained experimentally from solar powered electric cooker and other cooking medium was compared and recorded. 302 KJ quantity of heat is required in 22min to boil 1 kg of water. From calculations and observation, it has been proved that heat loss due to radiation was the highest followed by conduction and convection.

1. Introduction

Modern civilization has increased the standards of living of most people and has as well increased the demand for fossil fuels and electricity. Generally, energy is necessary as an

input to all machines and very large amount of energy is required for cooking purpose and that energy is extracted from conventional energy sources which are quite limited in supply. Cooking involves the use of solid fuel and non-solid fuel. Solid fuel which consists of coal which is a fossil fuel and biomass fuel (BMF) like (wood, charcoal, dung and crop residues). Worldwide, more than three billion people depend on solid fuels, including biomass (wood, dung and agricultural residues) and coal to meet their most basic energy needs: cooking, boiling water and heating. The non-solid fuel consists of kerosene, liquefied petroleum gas (LPG), and electricity. (Staton and Harding, 2000).

*Corresponding author, e-mail:author@fupre.edu.ng
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According to world health organization (WHO) reports, in 23 countries 10% of deaths are due to just two environmental risk factors: unsafe water, including poor sanitation and hygiene; and indoor air pollution due to solid fuel usage for cooking. In under-developed countries, women have to walk 2kms on average and spend significant amount of time for collecting the firewood for cooking. The cooking energy demand in rural areas of developing countries is largely met with biofuels such as fuel wood, charcoal, agricultural residues and dung cakes, whereas LPG or electricity is predominantly used in urban areas. It is also emphasized by the World Health Organization (WHO) that 1.6 million deaths per year are caused by indoor air pollution. Therefore, there is a rising attention concerning the renewable energy options to meet the cooking requirements of people in developing countries. Utilization of solar cookers provides many advantages like no recurring costs, high nutritional value of food, potential to reduce drudgery and high durability (Erdem and Pinar, 2013).

High cost of modern-day exploration techniques coupled with the devaluation of currencies of most developing countries like Nigeria, has made the price of petroleum products so high that most homes cannot afford it anymore. The coming of modern civilization has increased the standards of living of most people and has as well increased the demand for fossil fuels and electricity, thereby further increasing its cost. The increase in population has increased the demand for wood fuel and this has caused a lot of deforestation, which has resulted in serious desert encroachment and environmental hazards (Abdulkarim et al, 2016).

This paper is therefore meant to address the challenges arising from the shortcomings related to the use of electrical energy and help to eliminate the cost and reduce the over dependence of fossil fuel while maximizing the performance of maintenance free system. The solar cooker to be constructed and implemented, consists of five parts: Resistance heating alloy, battery, charge controller and a Photovoltaic panel.

Quite a number of evolutional works on solar cooker has been done over the years, employing different methods. The various designs have their own strengths and weaknesses, which would be evaluated in this brief review to fully distinguish one work from another. Ibrahim and Victor, (2016) designed a hybrid indirect solar cooker with latent heat storage using evacuated tube collector and latent thermal storage unit and alternate electric heating source. In their design, supply of energy was two ways, firstly energy is supplied by the heat transfer fluid to the cooking pot and secondly energy is supplied by electrical means. The heat transfer fluid which gets heated in the evacuated tube collector was supplied by heat transfer fluid to thermal storage unit by natural convection process. The phase changing material takes heat from working fluid and this heat is used for cooking during off shine and night hours with the inclusion of a heat exchanger. The hot working fluid flows in upwards direction because of thermosyphon phenomena. The vacuum in the evacuated tube collector allows the tube to act both as a super greenhouse and an insulator. This design allows to cook food inside the kitchen and also helpful to keep food warm till late night hours, but it has a drawback whereby the thermo transfer fluid must be change at intervals to keep the process running.

Gawali and Papade, (2015) developed a solar cooker using reflectors and DC heater. The system consists of thermal energy storage tank in which solar thermal energy is stored in the form of sensible heat by using different types of oils. Also, auxiliary DC heater is installed in the tank which is operated by using PV panels and battery. By using parabolic reflector, solar collector is used to concentrate solar energy at focal point on the thermal storage tank. Heat storing fluid is heated to its highest temperature based on several variables including area of the collector, emissivity, absorptivity, reflectivity and boiling/smoking temperatures. As the oil near focal point is heated, its density decreases, so this heated oil moves up in thermal storage tank and this space is occupied by cold oil. In this way total quantity of oil available in tank is heated by using natural circulation phenomenon. When solar intensity decreases, then insulation is applied to the tank to restrict the heat loss from the tank to the atmosphere. The system employs auxiliary DC heater which is dipped into the oil. This heater is operated on the batteries which will get charged by using PV panels.

One major drawback of the system is the use of oil which needs to be changed continuously as the heating oil tends to lose its heating power by usage. Chidi, (2011) designed and constructed a wooden solar box cooker using cheap and locally available material such with an efficiency of 72% from the various experiments that were carried out. The highest temperature gotten both on the ground floor and at the top of the roof was 72^0C both on the days with air temperature of 38^0C and 35^0C respectively. The inner part of the box is painted black to absorb the heat and trap the heat needed for cooking. Since black surface is a good emitter and absorber of radiation. The black surface absorbs all the radiation that falls on it, but reflects, and transmits none. The radiation that was refracted by the glass is absorbed by the black plate and converted to heat. The mirrors serve as reflectors. Inside the box is a mechanism which makes the mirror slant at an angle as soon as it is slotted into the groove made for it and when radiation from the sun is incident on the mirror, it is reflected in the opposite direction in such a way that it is absorbed by the glass on top of the box which serves as the lid. One major drawback of the system was that it does not employs energy storage system. Leary et al, (2019) developed four prototyped solar cookers for Kenya. The four prototypes constructed with each having slightly different design philosophies:

The eCook Kenya Mark 1 Prototype simply needed to show that battery-supported cooking was possible. It was built on a very low budget, using readily available components from conventional suppliers. It used 1kWh lead acid battery storage charged from an AC battery charger. Off-the-shelf AC cooking appliances were powered using an inverter. However, it could only operate at high power (1.2kW) for under 10 minutes, as lead acid batteries are not well matched with high C-rate applications such as eCooking. The second type developed for Kenya is the eCook Kenya Mark 2 Prototype (the eCook Box) was designed to showcase the superior performance of lithium ion. It replaced the Mark 1’s 1kWh lead acid battery storage with 1.2kWh LiFePO4, greatly extending the amount of time it could operate. This prototype was used to cook a blend of Kenyan and international dishes for 2 people for 1 year, powered by a blend of solar and grid electricity via a battery charger. However, it was still very bulky and heavy. The eCook Kenya Mark 3 Prototype (the eCook Bucket) was the third design for Kenya. It was designed to show how simple a solar electric cooking system could be. In the same way that solar lanterns integrated the whole system into a single unit, the eCook Bucket used a DC cooking appliance and integrated 0.24kWh LiFePO4 battery-storage into the body of the appliance, leaving just the PV panel outside. However, it was not possible to take this on an aero plane due to restrictions on travelling with higher capacity lithium-ion batteries. The eCook Kenya Mark 4 Prototype upgraded to the ultra-efficient Electric Pressure

Cooker (EPC) and was designed for showcasing at international conferences, with the LiFePO4 storage transported as a power bank in hand luggage.

1. Materials and Methods

2.1 Materials

Figure 1. shows the block diagram of the design specifically indicating how each of the system integrates with one another. The input - output approach was used, which consists of:

i. Input unit – Photovoltaic panel and charge controller
ii. Storage unit – battery

Output unit – resistance heating alloy

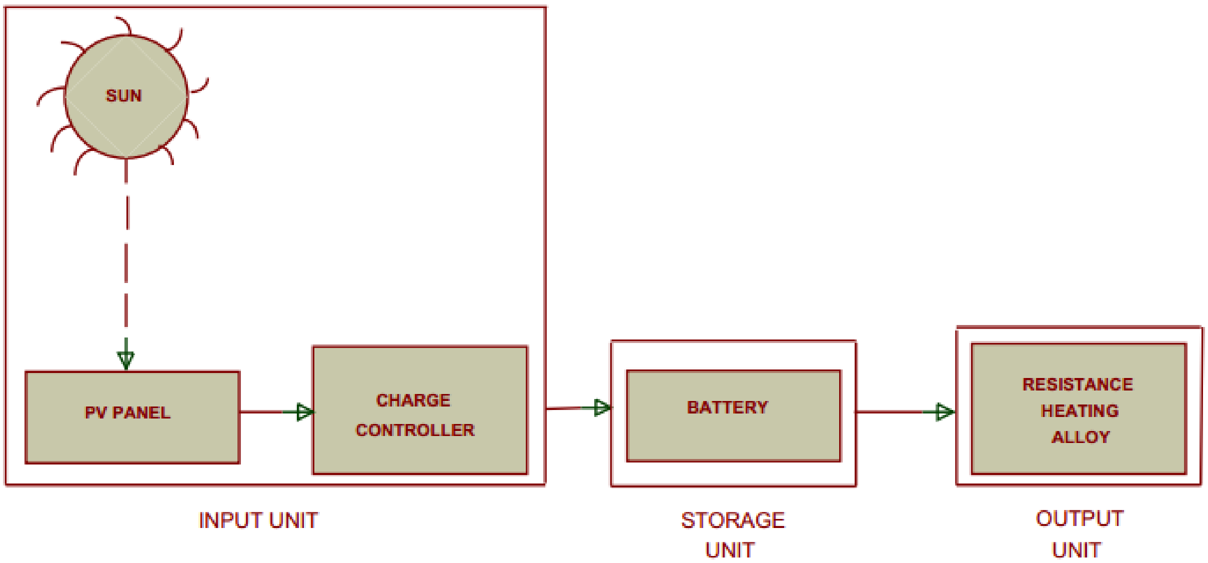

Figure 1. Block diagram of the system

2.1.1.1.Charge Controller

A **solar charge controller**, also known as a

solar regulator, is a small box consisting of solid-state circuits PCB which is placed between a solar panel and a battery. Its function is to regulate the amount of charge coming from the panel that flows into the battery bank in order to avoid the batteries being overcharged. Solar charge controller limits the voltage from the solar panel and regulate the same so as not to overcharge the battery; that is not to allow the battery to get into deep discharge mode while dc loads are used and to allow different dc loads to be used and supply appropriate voltage.

2.1.1.2. Photovoltaic Panels (Pv Panels)

A PV module is an assembly of photo-voltaic cells mounted in a framework for installation. Photo-voltaic cells use sunlight as a source of energy and generate direct current electricity. A collection of PV modules is called a PV Panel, and a system of Panels is an Array. Arrays of a photovoltaic system supply solar electricity to electrical equipment.

Solar photovoltaic cells or PV cells are made using silicon crystalline wafers which are similar to the wafers used to make computer processors and silicon chips. Silicon wafers are made using several different manufacturing methods with the most common being the Czochralski process. This process produces the more efficient monocrystalline cells although it is more energy intensive and thus the cost is higher. Polycrystalline cells, which is slightly less efficient, are made using the lower cost and easier casting method. More recently, a 'cast mono silicon or cast mono manufacturing process has been gaining popularity which is a lower cost method of making monocrystalline cells using a process similar to polycrystalline cells. However, cast-mono cells are not quite as efficient and pure mono cells. (Cleanenergyreview, 2020).

2.1.3 Battery

A battery is a device consisting of one or more electrochemical cells with external connections for powering electrical devices such as flashlights, mobile phones, and electric cars. When a battery is supplying electric power, its positive terminal is the cathode and its negative terminal is the anode.

The chemical reaction in the battery usually causes a buildup of electrons at the anode. This results in an electrical difference between the anode and the cathode. This difference can be thought of as an unstable build-up of the electrons. The electrons want to rearrange themselves to get rid of this difference. But they do this in a certain way. Electrons repel each other and tends to move towards the cathode. But the electrolyte keeps the electrons from going straight from the anode to the cathode within the battery. When the circuit is closed a wire connects the cathode and the anode and the electrons flows to the cathode. The electrons go through the wire and lights a bulb or any DC load along its path. (Northwestern, 2020)

2.1.4. Heat Resistance Alloy

Nichrome is the oldest form of resistance heating alloy. A common alloy is 80% nickel and 20% chromium, by mass, but there are many others to accommodate various applications. It is silvery-grey in color, is corrosion-resistant, and has a high melting point. Due to its resistance to oxidation and stability at high temperatures, it is widely used in electric heating elements, such as in appliances and tools. Typically, nichrome is wound in coils to a certain electrical resistance, and current is passed through it to produce heat. This resistance alloy is employed in this design because of the above excellent qualities it possesses.

2.2. Design Analysis and Implementation

The design of this work was done with certain specification in mind in order to achieve the desired results. The specification is outlined in table 1.

Table 1. Design Specification

Parameters	Specifications
Internal diameter of the cooker chamber	0.2m
Outside diameter of the cooker chamber	0.29m
height of the cooker chamber	0.12m
Internal Surface area of the cooker chamber	0.6m²
Area of cooking unit	2.86m²

The cooking chambers together with the battery and charge controller are coupled together.

A 5mm heat resistance coated glass is placed on top of the cooking chambers, so that the heat does not get direct contact with the user and immediate environment.

2.2.1 Determination of Sun Energy Output

Surface area of imaginary sphere is given by equations (1) and (2):

$$A_s = 4\pi r_s^2 \quad (1)$$

And

$$A_E = 4\pi r_E^2 \quad (2)$$

Assuming the average distance of the sun from earth = 1.5×10^8 km (Folaranmi, 2009).

Now, considering a sphere of radius 1.5×10^8 km with the sun at its Centre.

Let A_S = Surface area of this imaginary sphere,

And

A_E = Cross sectional area of the earth

r_s = radius of the sphere, r_E = radius of the earth

Where $r_E = 6.4 \times 10^6$ km, $r_s = 1.5 \times 10^{11}$ 10km

$$A_E = \pi r_E^2 = 3.142(6{,}4 \times 10^6)^2 = 1.287 \times 10^{11} m^2$$

$$A_E = 4\pi r_E^2 = 4 \times 3.142(1.5 \times 10^{11})^2 = 2.828 \times 10^{23} m^2$$

Percentage of Sun's output is given in equation (3).

The implication is that the earth receives 00000000455% from the sun energy.

2.2.2. Determination of Extraterrestrial Radiation in Nigeria

Folaranmi, (2009) studies on radiation of the sun indicates that it varies from region to region. Extraterrestrial solar radiation in Nigeria can be calculated using the equation 4:

$$R_X = I_{XC} A_{CL}$$

Were,

Rx = extraterrestrial radiation,

A_{CL} = continental area,

I_{XC} = solar constant

Given their equivalent as;

Rx = $1.262 \times 10^{15} W/m^2$

I_{XC} = 1353kWh

A_{CL} = 932768 x 10^6

Assuming a yearly average sunshine hour of 9 hour per day

$$R_X = 1353 \times 10^3 \times 932768 \times 10^6 \times 3.26$$

$$R_X = 1262 \times 10^{15} \times 366 \times 9$$

Therefore,

Taking a clearness index of 50%, since only 47% of extraterrestrial radiation reaches the earth surface and terrestrial radiation in Nigeria land area (Folaranmi, 2009).

Calculating,

Rx = [(50/100) ×4.157 ×10^{18}] = 2.079 × 10^{18} *Wh*/year

To calculate the direct radiation reaching the earth surface
as a function of time of the day (t), for location (γ) with the sun at
declination angle (δ)

Let,

Z -zenith angle,

γ -Latitude of location,

δ - Declination angle,
t-hour angle of the sun.

Iz - direct solar radiation,

I_{XC}-extraterrestrial solar radiation constant,

I_h - horizontal radiation

x and c are given as the climate graphical determined constants.

Equation 5 is the zenith angle given by:

$$Cosz = Sin\gamma Sin\delta + Cos\gamma Cos\delta Cost 3.27$$ (

$$Cosz = Sin14^0 Sin0^0 + Cos14^0 Cos0^0$$

$$Cosz = 0.2192 \times 0 + 0.970291 \times 1 = 0.97029$$

$$Z = Cos^{-1}(0.97029) = 14^0$$

After passing through the atmosphere, the solar radiation is given in equation 6 thus:

$$I_Z = I_X e^{-C(SEC\,Z)X}$$

$$I_Z = 1353 e^{-0.357(1/_{COS 14})0.678} = 940 w/m^2$$

Therefore,

I_Z = 940 w/ m^2

I_Z is the maximum value of direct radiation incident on a normal surface, and this maximum value can only be gotten by system that automatically track the sun's radiation.

Cooker Efficiency

The efficiency of the cooker was calculated using equation 7.

$$\eta = \frac{Q_{out}}{Q_{in}} = \frac{Q}{I_b A t}$$ (7

where,

Q = Quantity of heat needed to cook the meal (J)

I_b = heating alloy insolation (W/m^2)

A = Cross sectional area of cooker unit (m^2)

t = Cooking time (sec)

Assuming,

Quantity of heat needed to boil 1litre of water = 302.4KJ

I_b = 600.24W/m^2

A = 2.86m^2

t = 10mins

Therefore,

η = 907.2 x 10^3 / 600.24 x 2.86 x 600

= 88%

Determination of heat losses by the system

Heat lost due to convection in the system

The heat lost by convection is given as:

$$Q = H_c A(\theta_f - \theta_i) \quad (8)$$

Where H_c = convection heat transfer coefficient = 28.5 W m^{2}V°C

Q = 28.5×8.90×10ÉT×74

Therefore, heat loss by convection is 1.8770J

Heat lost by conduction in the system

Equation 9 gives the heat loss by conduction

$$Q = \frac{KA}{X}(\theta_f - \theta_i) \quad (9)$$

Were,

K = Coefficient of thermal conductivity for mild steel = 48.5 W m^{2}V°C

Assuming the temperature of the pot is in thermal equivalent with the system

X = thickness of the pot = 3mm

$A = surfaceareaofthepot = 2\pi(R^2 - r^2) + 2\pi(R - r)h$

Were,

R = Outer radius of the pot = 0.29m,

d = inner radius of the pot = 0.2m,

h = height of the pot = 0.12m

Computing values,

A = 2×3.142× (0.29^2 − 0.2^2) + 2×3.142 (0.29− 0.2) × 0.12 = 9.06 × 10^{-1}

Therefore,

$$Q = \frac{48.5 \times 9.06 \times 10^{-1} \times 74}{3\times10^{-3}}$$

Q = 1.08kJ

Heat lost by radiation

Heat lost by radiation is given in equation (10)

$$Q = \sigma AT^4 \quad (10)$$

Were,

Where T= temperature of the solar cooker which is assumed to be in thermal equilibrium with the mixture at 102 + 273 = 375K

σ = Stefan Boltzmann constant (5.67×10^{-8})

A= area of the solar cooker

Therefore,

Q = 5.67×10^{-8} × 2.86 × 375^4 = 3206.8J

Q = 3.2kJ

Conclusively, from calculations and observation it has been proved that heat loss due to radiation was the highest followed by conduction and convection.

Figure 2. Shows the complete work after implementation.

Figure 2. System in its working state

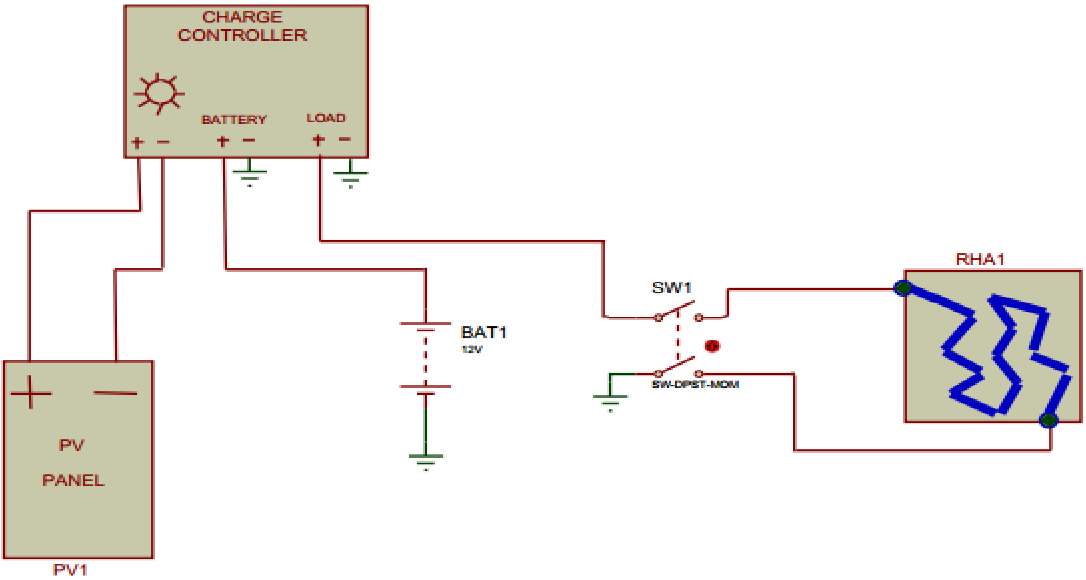

Figure 3. ***Circuit diagram of solar powered battery cooker***

2.1. Mode of Operation of Solar Powered Electric Cooker

Figure 2 shows the battery solar cooker which consists of four main parts; the heating chamber, the battery, the charge controller and solar panel with its stand.

The cooking chambers together with the battery and charge controller are coupled together.

A 5mm heat resistance coated glass is placed on top of the cooking chambers, so that the heat does not get direct contact with the user and immediate environment.

Whenever the switch connected to the system in its ON position, the heated element gradually gets heated up and is set for usage.

The charge controller has an inbuilt mechanism that helps to monitor the battery level and whenever the level drains below 10VDC it cuts off the battery from the system to avoid further drains.

2. Test, Result and Discussion

Performance evaluation was carried out using digital thermometer and 1 kg of water. The quantity of heat needed to boil the water, as well as the cooking time was calculated and recorded as shown in table 2. The solar electric cooker system was compared against other means of cooking such as the gas cooker and the kerosene stove under the same environmental conditions. From the results obtained, it was observed that it took the gas cooker 732kJ of heat to boil 1kg of water in 14minutes, the kerosene stove took 416kJ of heat to boil 1kg of water in 29minutes while the Solar electric cooker took 302kJ of heat to boil the same quantity of water in 22minutes. Comparing the results, it was observed that the solar electric cooker took the least amount of heat to boil the same quantity of water and therefore is the best as it presents a clean source of energy with no effect on the environment.

Tabular Representation
Table 2

S/N	Cooking Medium	Meal	Quantity of Heat (kJ)	Time Taken to Boil (Min)
1.	gas cooker	1kg water	732	14
2.	kerosene stove	1kg water	416	29
3.	Solar electric cooker	1kg water	302	22

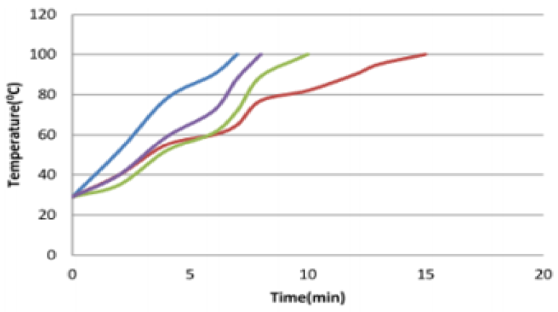

Figure 4. Graphical Representation of different cookers and Temperature variation

Where,
Green – Wood Burner Cooker
Red – Kerosene Cooker
Pink – Battery Solar Cooker
Blue – Gas Cooker

The results obtained from the solar cooker met the design requirements. The thermal efficiency was high and remained relatively stable within slight changes in the battery voltage supplied. Table 2 and Figures 4 shows the variation of heating rate against cooking time for water across the various cooking medium. From the test analysis gas cooker takes a shorter time compared with the battery cooker and the kerosene stove which take a longer time. However, the Solar Electric Cooker use 302KJ of heat energy to boil the same quantity of water compared with the Gas Cooker and the Kerosene Cooker which are 732KJ and 416KJ respectively. On the whole the Solar Electric Cooker is better compared with the others cookers from the result obtained. This will help to maintain a clean environment for mankind.

Conclusion

The conceptualization of this work provides a convenient and good alternative to conventional domestic ways of cooking. With the sole aim of reducing the effect other cookers have in the environment such as deforestation and emission of greenhouse gases. From the results obtained above, it was clear that the solar electric cooker is the best source of cooking that can help to maintain a clean environment for mankind. Other sources of cooking produce harmful gaseous emission to the environment thereby making it unsafe for mankind and increasing the greenhouse effect.

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