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Design and Performance Evaluation of a Parabolic Solar Cooker for Rural Communities in Eastern Nigeria

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Abstract
This study aims to design and construct a domestic solar cooker using locally available materials. The heat from the sun was concentrated on a parabola with a reflecting surface to a black casted Aluminum plate (absorber) located at the parabola's focal point. The heat absorbed was utilised for cooking. The research was designed to cook about 2.5kg of beans, a staple food requiring more heat energy than most foods. The design was to produce a cooker that can give 2616kJ of heat energy, considering the solar insolation of Owerri, the Eastern heartland of Nigeria. The Diameter of the dish that can trap this amount of energy is 1.7m. The focal distance where the pot was mounted was calculated to be 0.747m from the centre of the parabola. This work is modelled with Autodesk Inventor. Performance evaluation was done with different meals cooked and the heating rate calculated. The exact quantity of raw food cooked with other mediums and the heating rate were calculated. Comparisons were made, and it was obvious that the solar cooker was most suited for rural areas and people living in areas with high average solar intensity. The efficiency of the solar cooker is 33%. This invariably means that 33% of the energy in the solar cooker was used for cooking.
Keywords: Solar cooker, Solar energy, Renewable energy, Alternative energy, and environmentally friendly solutions

Introduction

Solar energy is the free, abundant energy from the sun which is exploited through different means and processes. The Earth obtains 174 pet watts (PW) of entering solar radiation. Approximately 30% is reflected in space, while clouds, oceans and land masses absorb the rest, Singh and Mishra (2015). The solar light spectrum at the Earth's surface primarily ranges across the observable and near-infrared ranges, with a small part in the near-ultraviolet, Singh and Mishra (2015). The continuous rise in greenhouse gas (GHG) emissions and the cost of premium motor spirit are the main driving forces to utilise various renewable energy sources. Amid the clean energy technologies, solar energy is recognised as one of the most promising choices since it is free and offers clean and environmentally friendly energy. The Earth receives 3.85 million KJ of solar energy yearly, Rasheed *et al.*, (2022). Solar energy offers various applications to harness this available energy resource. Among the thermal applications of solar energy, solar cooking is considered one of the simplest, most viable and attractive options for utilising solar energy. Solar cookers suggest clean and free cooking, which is attractive for modern urban life as an alternative to accessible and clean energy in rural areas and for people in developing countries grappling with a lack of energy. In Nigeria, as in many developing countries, the high costs of modern cooking energy such as Liquid Petroleum Gas (LPG) and electricity and their cooking stoves are significant constraints for household fuel preferences. Isara and Aigbokhade (2014). The poor economic situation and the epileptic and poor electricity supply compound this. These have resulted in the use of fossil and solid fuels (biomass and coal) as significant sources of cooking energy. Diseases due to air pollution from cooking remain a primary cause of respiratory morbidity and mortality worldwide, in sub-Saharan Africa and Nigeria (NBS, 2014). The use of solar cookers will mitigate these challenges. The parabolic solar cooker designed and constructed in this study used the incident rays from the sun, reflected by a solar reflector and concentrated at a point to cook staple foods. Manish and Dheerandra (2018) evaluated the thermal performance of solar cookers using two different materials for the cooking vessel, Aluminum and GI sheet, the values of heat loss factor, optical effectiveness factor, cooking power, sensible cooking power, average sensible efficiency, and exergy efficiency were analysed, and based on these performance factors, he concluded that Aluminum vessel is better than galvanised iron. Singh *et al., (*2018).

Yahya (2016) utilised the new world standard procedure for testing solar cookers to determine the thermal performance of a concentrating solar cooker, and he concluded that between 9.00 am and 4.00 pm is the most suitable time range for cooking. Akoy *et al.* (2015) designed and constructed different types of solar cookers: box, panel, and parabolic. They adopted the standard procedure for testing solar cookers to test the thermal performance of the constructed solar cookers. The thermal performance results showed that the parabolic solar cooker attained the maximum temperature on an average basis and was the best followed by the box type and panel type. Osueke *et al.* (2013) studied solar irradiance in four locations in Nigeria (Enugu, Lagos, Abuja and Maiduguri). The model showed that solar irradiance is more prevalent in Maiduguri when compared to Enugu, Lagos, and Abuja and should be a better site for the usage of solar cookers. In all the literature reviewed, the conclusions of previous researchers in the area of solar cookers guided the choice of design decisions made in the construction of the cooker. However, there is inadequate information regarding the performance evaluation of solar cookers and other cooking mediums. This is necessary because the data from the work will guide households in deciding on the best cooking medium for cooking time, affordability, accessibility, etc.

Materials and Methods

The cooker consists of three main parts: the pot, the parabolic dish, the dish stand and the base. The cooking pot, the holder and the parabolic dish are mounted on a frame supported by the shaft and the base. The parabolic dish is fixed to the bracket to be rotated in the sun's direction. The glass mirror that serves as the reflector was glued onto the parabolic dish's surface. The choice of the pot was of primary importance; it is painted black, and a black surface absorbs all radiation that falls on it but transmits none. The radiation refracted by the glass is absorbed by the black plate placed at the focal point of the parabolic dish and converted to heat.

Design Considerations

The solar cooker was designed to develop sufficient energy to cook 2.5kg of beans that is expected to feed a family of four. The heat energy required was determined by cooking this quantity of beans using the conventional method of cooking and taking measurements of the initial and final temperature of the beans.

Diameter of the dish

The Diameter of any circular object is the distance from one end of the object to another. The Diameter of the dish was designed to meet the design requirements, that is, developing a sufficient quantity of heat to cook 2.5kg of beans. The Diameter directly relates to the surface area, determining the quantity of heat the dish can reflect.

The quantity of heat required to cook beans is given by equations 1 and 2:

$$Q = Q_b + Q_w \quad \text{(Ling } et\ al. \text{ 2016)} \ldots. \ (1)$$

$$Q = M_b C_b(\Theta_f - \Theta_i) + M_w C_w(\Theta_f - \Theta_i) \ldots\ldots \ (2)$$

Where,

M_b = mass of beans (kg)

M_w = mass of water (kg)

C_b = specific heat capacity of beans (j/kg°C)

C_w = specific heat capacity of water (j/kg°C)

Θ_i = initial temperature of the mixture (°C)

Θ_f = final temperature of the mixture (°C)

Also, heat flux is given by equation 3

$$\dot{q} = \frac{Q}{A} \quad \ldots\ldots. (3)$$

For a radiative surface, heat flux is given by Equation 4

$$\dot{q} = \varepsilon\sigma\Theta_f^{\,4}$$ (Ling *et al.,* 2016), (Ganji *et al.,* 2018) …….. (4)

Therefore, from equation 3 and 4, equation 5 is obtained.

$$A = \frac{q}{\varepsilon\sigma\Theta_f^{\,4}} \quad \ldots\ldots(5)$$

Where,

A = surface area (m^2)

ε = emissivity of a plane mirror

σ = stefan boltzman constant

Also, the cross-sectional area of the parabola is defined by equation 6.

$$A = \frac{\pi D^2}{4} \ldots\ldots\ldots (6)$$

Where, D = Aperture diamter (m^2)

Therefore, from equations 5 and 6, equation 7 is obtained.

$$D = \frac{4Q}{\pi\varepsilon\sigma\theta_f^4} \quad \ldots\ldots(7)$$

This formula was used to calculate the Diameter of the parabola.

D = 1.77m

Length of the Shaft

The length of the shaft was designed so that it can support the given load effectively without buckling. The shaft is treated as a column.

According to Euler, the buckling load is defined by equation 8.

$$W_{cr} = \frac{\pi^2 \in I}{I^2} \quad \ldots.(8)$$

(Kuzkin and Dannert 2016)

E = modulus of rigidity or young modulus for the material of the column

I = moment of inertia of the cross section.

L = equivalent length or effective length of the shaft

But, for a column with both ends hinged, the equivalent length (L) is equal to the actual length (I)

Therefore, from equation 8, equation 9 was obtained.

$$I = \sqrt{\frac{\pi^2 EI}{W_{cr}}} \ldots\ldots(9)$$

1.20m

Focal point: The focal point is also known as the focus of a parabola. The parabola is a set of all points in a plane that are an equal distance from a given point. This point is the focus or the focal point of the parabola. For the parabolic solar cooker, this point is where the rays reflected by the reflector appear to be concentrated. Mathematically, the focal point is calculated using equation 10.

$$f = \frac{D^2}{16h} \quad \ldots.. \ (10) \ (\text{Ling et al., } 2016)$$

Where D= Diameter of the dish and h =height.

f = 0.747m

Materials Selection

The material selection was based on Ashby's book, which stated that material is inherently based on at least five inter-related criteria (Onokwai *et al.* 2019) such as:

i. The function of structural component
ii. Materials available and their properties
iii. Shape and size of structural component
iv. The process used to manufacture structural component
v. Cost and Availability (of both material and process)

A complete understanding of the functions of all cooker parts is essential. The essential parts of this cooker include;

i. Parabolic dish
ii. Bracket
iii. Castor wheel
iv. Dish stand
v. Absorber plate
vi. Reflecting mirror

Table 1 shows the different materials used for each cooker part.

Parabolic dish

The parabolic dish collects solar radiation over a large area and concentrates it onto a small area, the focal point, where the food's absorber plate contains the food. To develop sufficient heat required to meet the design requirements, the Diameter of the parabolic dish was designed and constructed as 1832.40mm, and the depth is 280mm. The reflectors are glued onto the surface of the parabola, as shown in Figure 1.

Bracket

The bracket provides the means of hinging the parabola to rotate freely towards the sun's direction. It also links the parabola to the dish stand, as shown in Figure 2.

Dish stand

The dish stand supports the dish and connects it to the base. It is welded rigidly to the base, according to the design; it has a total length of 625mm, with the lower end (end welded to the base) having a diameter of 90m. The upper end (the end fitted to the bracket) has a diameter of 70mm; this Diameter runs through the length of 135mm, which is the end fitted to the bracket shown in Figure 3.

The base of the cooker

A mild steel angle iron was used for the base. The base carries and supports the components of the solar cooker. The length and breadth are 700mm with a thickness of 9mm, as shown in figure 4.

Reflecting Mirror

It is a glass mirror with a silver coating behind it, which was cut to cut so that the curvature of the parabola can be retained. The reflector reflects sun rays to the parabolic dish, as shown in Figure 5.

Castor Wheel and Absorber plate

It is a wheeled device typically mounted to the base that enables easy movement of the solar cooker. The absorber plate is the cooking pot, ideally painted black, to retain the heat from radiation. The Diameter is 241mm, and the length is 165mm, as shown in figure 6.

The assembly drawing of the heater is shown in Figure 7. The entire components of the solar cooker were mounted on the base after construction.

2.12 Principle of Operation

Most solar cookers work on the basic principle: Sunlight is converted to heat energy retained for cooking. Parabolic solar cookers typically require more frequent reorientation to the sun but will cook more quickly at higher temperatures and can fry foods. The constructed parabolic solar cookers use a parabolic dish in which a reflecting material is glued to focus the light more directly onto the cooking pot. It typically does not require a greenhouse enclosure to retain the heat. At its simplest, the sunlight-to-heat conversion occurs when photons (particles of light) moving around within light waves interact with molecules moving around in a substance. The rays emitted by the sun have a lot of energy in them. When they strike matter, whether solid or liquid, all of this energy causes the molecules in that matter to vibrate. They get excited and start jumping around. This activity generates heat. Dark surfaces get very hot in sunlight, whereas light surfaces don't. While the food cooks best in dark, shallow, thin metal pots with dark, tight-fitting lids, many other containers can also be used in a solar cooker. For this purpose, a black aluminium pot was used as the absorber plate. A transparent heat trap around the dark pot lets in the sunlight and keeps the heat that is produced from escaping. Heat is reflected as a longer wavelength and does not easily pass through the transparent enclosure. Parabolic solar cookers typically do not require a heat trap, as the light from the reflector is tightly focused on the cooking pot. They cook at higher temperatures but require more frequent reorientation with the sun than box or panel cookers.

Experimental setup and procedure

The constructed solar cooker was used to cook 2.5 kg of beans and rice, 1.8kg of yam and 1kg of water. Each mixture's initial and final temperature was measured with a thermometer every 15 minutes, the time taken to cook each food was taken using a stopwatch, and the quantity of heat needed to cook each meal was calculated. The various meals on the solar cooker were also cooked using different cooking mediums: gas cooker, kerosene stove, firewood, and comparisons.

Performance evaluation

Power of Heating/Heating Rate

The power of heating is the ratio of the energy used in cooking to the time used. The power required to heat a certain mass of beans is given by equation 11;

$$\text{Power} = \frac{E_c}{t} \quad \ldots\ldots(11)$$

Where E_c = energy used in cooking and t = time

But from equation 11, the energy required to cook a certain mass of beans is given in equation 12.

$$Q = M_b C_b(\theta_f - \theta_i) + M_w C_w(\theta_f - \theta_i) \ldots\ldots(12)$$

Therefore, the power required is obtained using equation 13

$$\text{Power} = \frac{M_b C_b(\theta_f - \theta_i) + M_b\, C_c\,(\theta_f - \theta_i)}{t} \ldots\ldots(13)$$

Power of heating = 0.386 watts

Heat flux

Heat or thermal flux is the amount transferred per unit area per unit of time from or to a surface.

Mathematically, it is defined as shown in equation 14,

$$q = \frac{H_E}{S_A} \ldots\ldots(14)$$

Where H_E = heat energy used in cooking and S_A = surface area of the cooker

The parabola surface area is given by equation 15

$$S_A = \frac{8\pi * f^2}{3}\left[\left[\left(\frac{D}{4 * f}\right)^2 + 1\right]^{\frac{2}{3}} - 1\right] \ldots\ldots(15)$$

Therefore, heat flux in the system is given by equation 16

$$q = \frac{M_b C_b(\theta_f - \theta_i) + M_w C_w(\theta_f - \theta_i)}{\frac{8\pi * f^2}{3}\left[\left[\left(\frac{D}{4 * f}\right)^2 + 1\right]^{\frac{2}{3}} - 1\right]} \ldots\ldots(16)$$

$q = 914 kj/m^2$

Efficiency of the cooker

This is the ratio of the energy used in cooking to the energy supplied by the solar cooker, as shown in equation 17.

$$\varepsilon = \frac{O}{I} \quad \ldots\ldots(17)$$

Where O = Output and I = Input

The energy supplied by the solar cooker is given by equation 18

$$Q = I_b \times A \times t \quad \ldots\ldots(18)$$

Therefore, the energy required to cook a certain mass of beans is given in equation 19.

$$\varepsilon = \frac{M_b C_b(\theta_f - \theta_i) + M_w C_w(\theta_f - \theta_i)}{I_b \times A \times t} \ldots\ldots(19)$$

$$\varepsilon = 33\%$$

Thermal Stresses

Given the standards of measurement, the values used to calculate the thermal stresses are stated as Linear expansivity for mild steel $(\alpha) = 12.0 \times 10^{-6}$

Modulus of elasticity $(\in) = 200\text{MPa} = 200 \times 10^6\ \text{N/m}^2$

Assuming that thermal stresses begin to develop at the temperature of (t) = 373k.

Then, the thermal stress induced on the plate is determined as in equation 20.

$$\sigma = \alpha \times t \times \in \cdots\ldots\ldots(20)$$

The thermal stress values on the plate were obtained as $895.2 \times 10^3 N/m^2$.

This value is below the allowable working stress for mild steel, which is $247 \times 10^6 N/mm^2$; therefore, the design is safe.

Results and Discussion

The performance evaluation result shows the cooking time for various meals using a solar cooker. 2.5kg of beans and rice were cooked, 1.8kg of yam and 1kg of water. The quantity of heat needed to cook each meal was calculated, and the time needed to cook the meal was measured. The various meals on the solar cooker were also cooked using different cooking mediums like gas cooker, kerosene stove, and firewood; comparisons are shown in Appendix Table A1 to A3. Figure 8 compares the heating rates of the various cooking mediums for rice, yam, beans and water. The gas cooker has the highest heating rate of the four cooking mediums, and the kerosene stove is the lowest. There's a slight difference in the heating rates for firewood and solar cookers. This suggests that on days when the solar intensity is higher or in areas with higher solar intensity, there's a huge possibility that the heating rate of the solar cooker will be higher than that of the firewood. Figures 8 to 12 show the temperature variation against cooking time for beans, rice, yam and water across the various cooking mediums. For all the meals, the gas cooker and firewood take a shorter time than the solar cooker, and the kerosene stove takes longer. The firewood is slightly faster than the solar cooker because firewood has uncontrolled combustion, and solar insolation is not at its peak at the time of the year when the experiments were carried out. The efficiency of the cooker was calculated and found to be 33%. That means the solar cooker utilises 33% of the energy that falls on it for cooking. The heat demand of the solar cooker was so it could cook about 2.5kg of beans that can feed a family of four. Beans take longer time to cook than other staple foods. The solar cooker was designed in such a way that it can effectively trap the quantity of heat needed to cook this food. Equation 3.6 was used to design the Diameter as 1.7m and constructed at 1.8m to compensate for heat losses. Factors considered in sizing the solar dish are the quantity of heat needed to be trapped, the emissivity value of a plane mirror and the temperature at which the food gets done. Another consideration is the focal distance, where all the rays converge. It is essential for maximum heating. Equation 3.9 was used, and it was found to be 0.747m. The pot was mounted at a distance of 0.747m from the centre of the dish.

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Conclusion

A parabolic solar cooker was constructed to mitigate the harmful effects of using non-renewable energy sources for cooking. From the results obtained through the experiments, it can be deduced that the cooker is highly suitable for cooking staple foods. The use of the cooker depends on environmental conditions, the time of the day in which cooking is done and the geographic location. Solar cookers cook foods for a considerable time compared to other cooking mediums. Shortly, solar energy will contribute a significant share in the energy sector. So, proactive utilisation of solar power is essential. The parabolic dish solar cooker represents a potential subsidiary way of cooking to the conventional ways. According to the design, the cooker was constructed with available materials in the local market. After construction, it was tested, and the cooker can cook 2.5kg of beans within 50 minutes at an available radiation level of 1320. So, the cooking efficiency of the cooker is satisfactory. Though its construction and operational costs are low, this type of solar cooker can be promoted in remote and rural areas. The government should partner with research agencies to produce solar cookers in large quantities in areas with sufficient sunlight, particularly in rural areas. This will prevent deforestation and preserve the natural resources. The government should also encourage research agencies to conduct more research on storing solar energy such that the cooker can be utilised during the night.

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Appendix

Performance Evaluation Results

Table A1: Heating rate of various cooking mediums for Beans

Cooking medium	Heat quantity(kj)	Time (sec)	Heating rate (kwatts)
Gas cooker	2616	4500 (75mins)	0.581
Stove	2616	7320(122mins)	0.357
Solar cooker	2616	6780(113mins)	0.386
Firewood	2616	6300(105mins)	0.415

Table A2: Heating rate of various cooking mediums for rice

Cooking medium	Heat quantity	Time	Heating rate
Gas cooker	2004.4	3900(65mins)	0.51
Stove	2004.4	6600(110mins)	0.304
Solar cooker	2004.4	5400(90mins)	0.371
Firewood	2004.4	4800(80mins)	0.418

Table A3: Heating rate of various cooking mediums for yam

Cooking medium	Heat quantity	Time	Heating rate
Gas cooker	1364.8	2400(40mins)	0.569
Stove	1364.8	4200(70mins)	0.325
Solar cooker	1364.8	3600(60mins)	0.379
Firewood	1364.8	3300(55mins)	0.413

Table 1: Materials used for parts of the cooker

S/N	Component	Material used
1	i. Parabola ii. Base iii. connecting shaft **iv.** bracket	Mild steel
2	Reflector	Glass mirror
3	Absorber plate	Aluminium

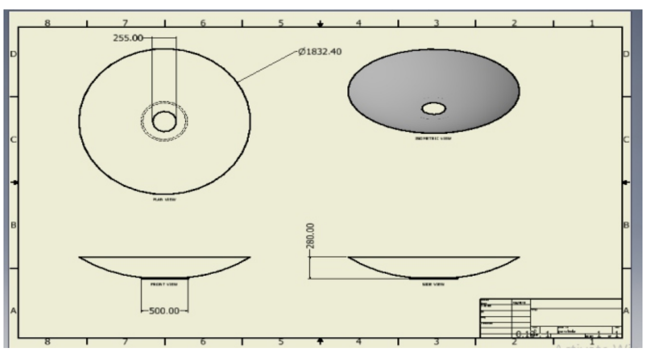

Figure 1: An orthographic view of the parabola

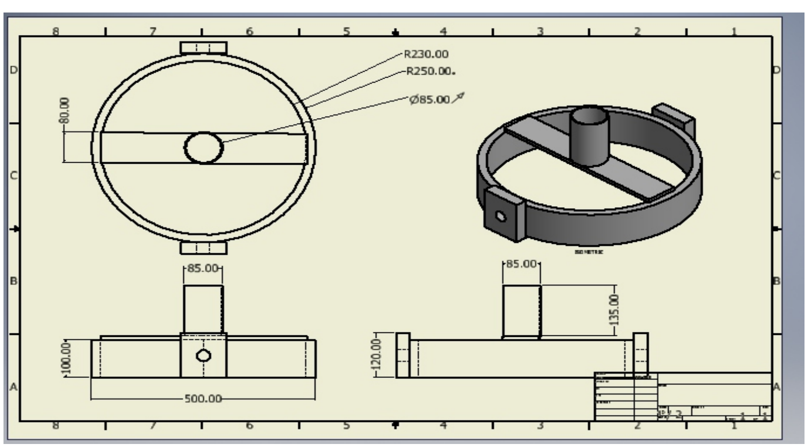

Figure 2: An orthographic view of the bracket

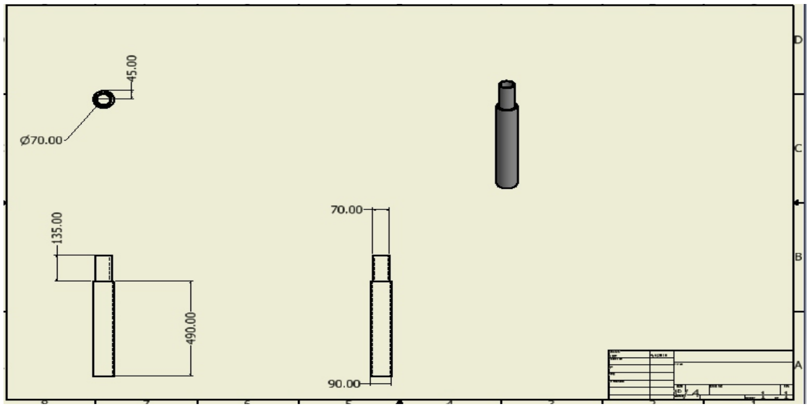

Figure 3: An orthographic view of the dish stand

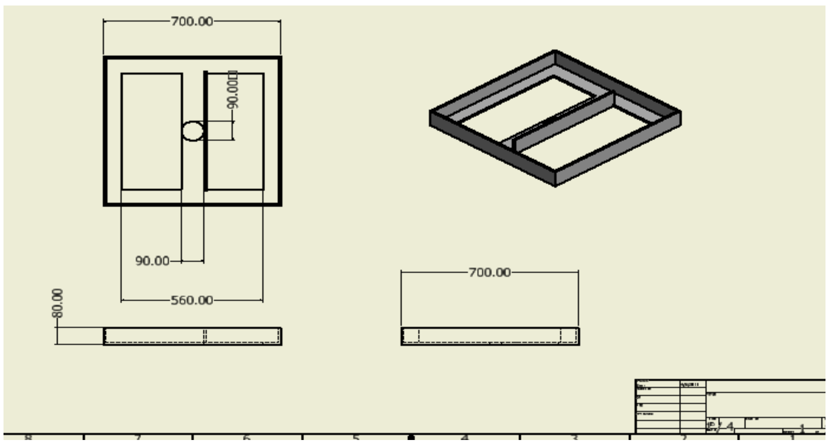

Figure 4: An orthographic view of the base

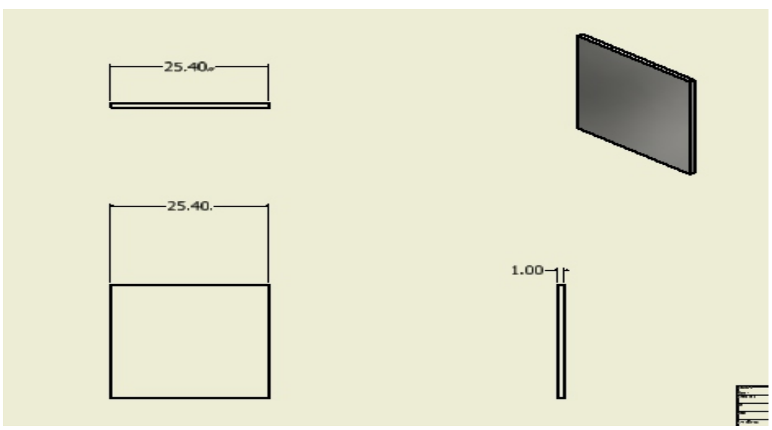

Figure 5: An orthographic view of the reflecting mirror

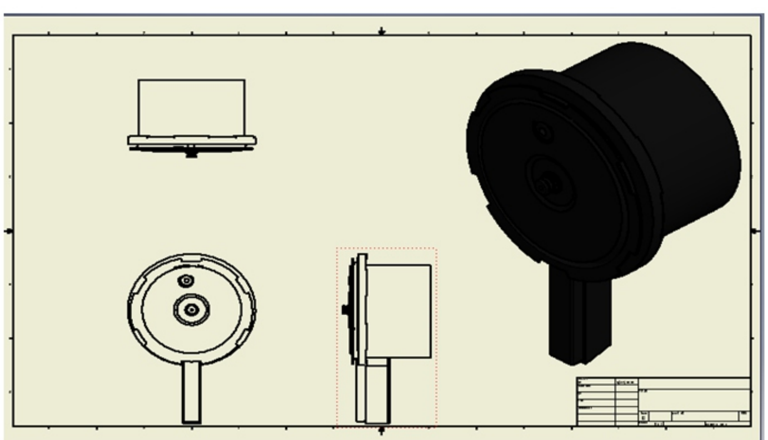
Figure 6: An orthographic view of the pot

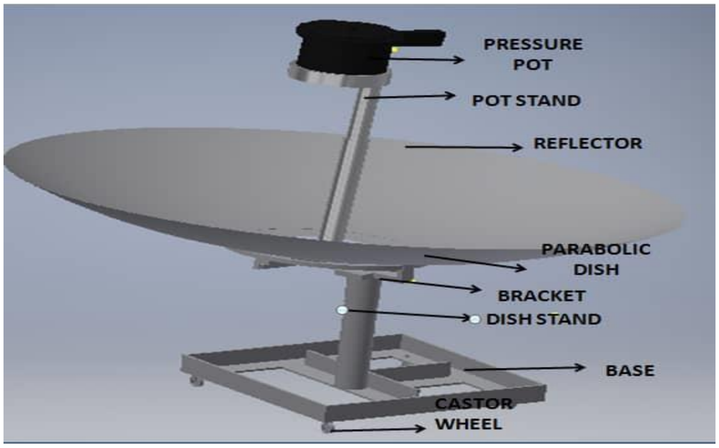

Figure 7: An assembly of the project

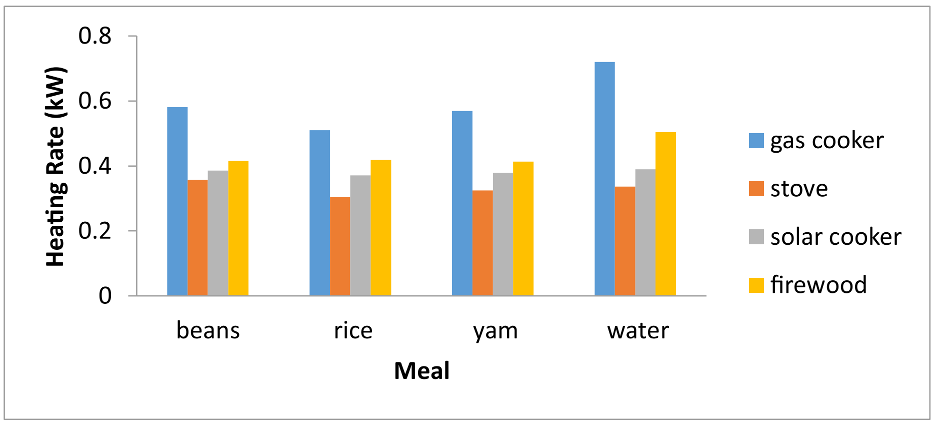

Figure 8: Graph showing the heating rate for various cooking medium

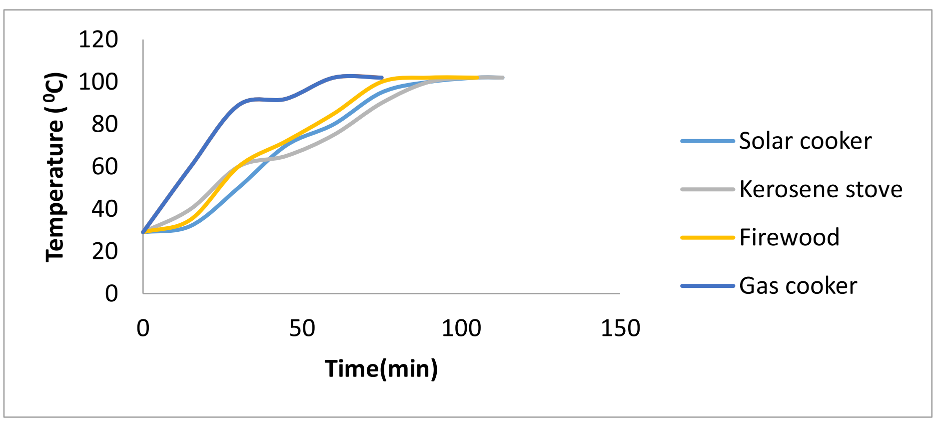

Figure 9: The variation of temperature against cooking time across the various cooking mediums for beans

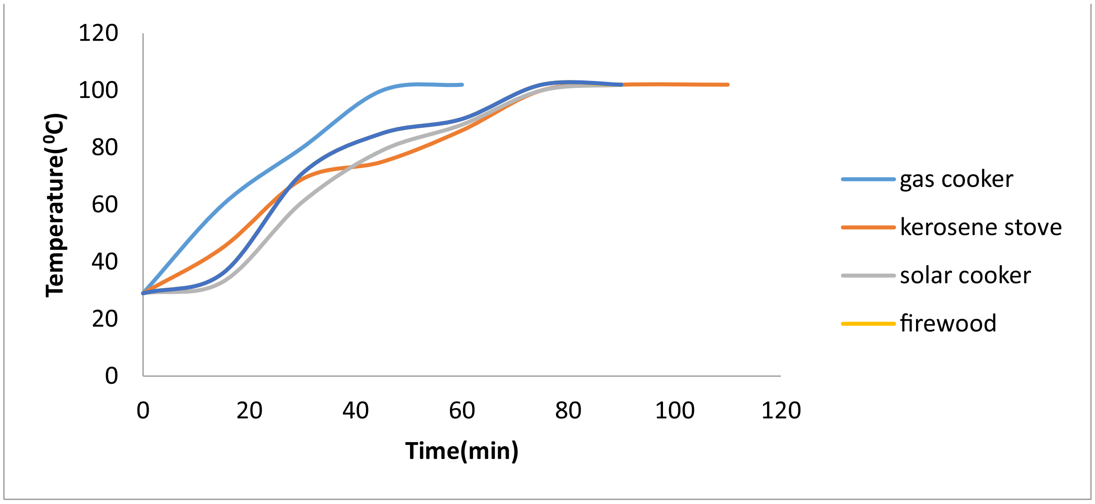

Figure 10: Variation of temperature against cooking time across different cooking mediums for rice

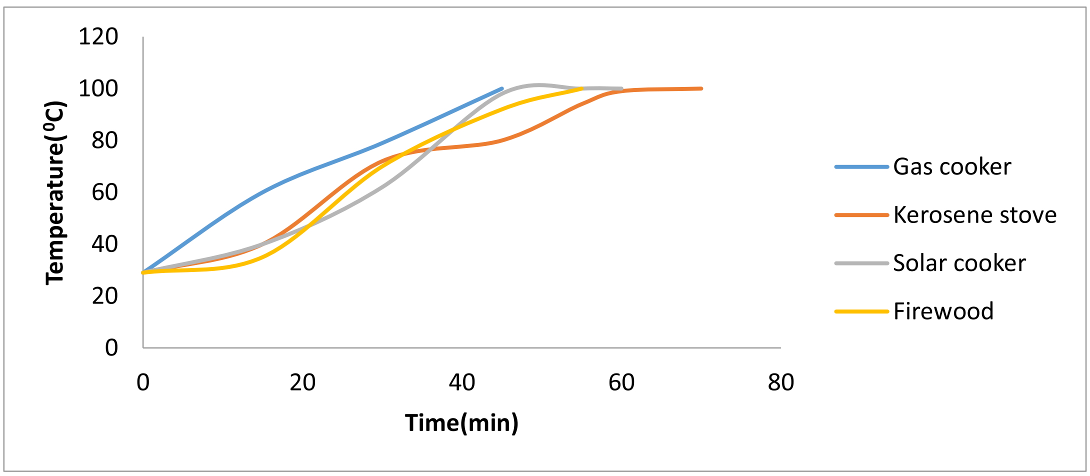

Figure 11: Variation of temperature against cooking time across different cooking mediums for yam

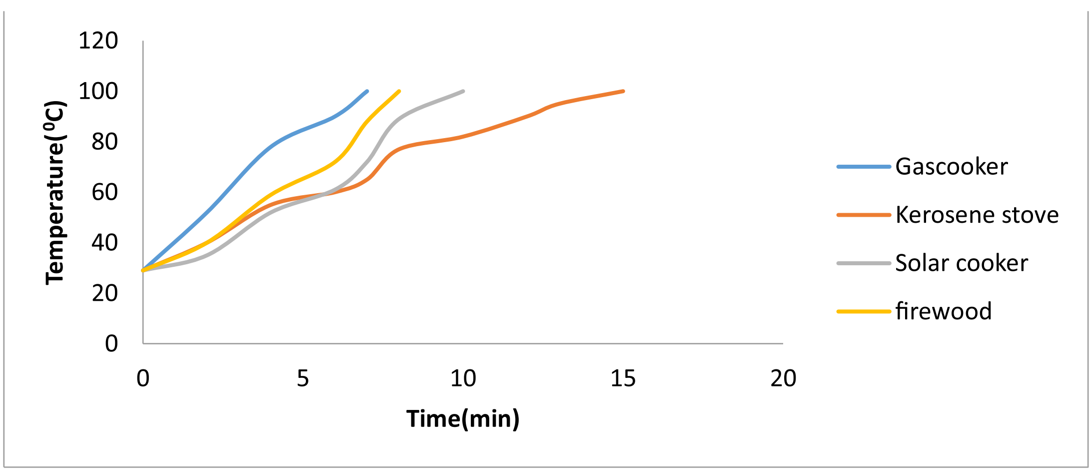

Figure 12: Temperature variation against cooking time across different cooking mediums for water