



Simulation, Construction and Performance Evaluation of Solar Box Cooker

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ABSTRACT

The values of first figure of merit (F_1) and that of the second figure of merit (F_2) were found to be 0.126 and 0.390 respectively. The values indicate the proper functionality of the solar box cooker. And the standardised stagnation temperature was found to be 104°C at an ambient temperature of 37°C and at solar radiation of $795.5\text{W}/\text{m}^2$. Also high solar intensity for experimental and simulation results were found to be $1070\text{W}/\text{m}^2$ and $1020\text{W}/\text{m}^2$ respectively. The co-efficient of determination (r^2) for both the simulated and experimental results were found to be 98.8% and 94.1% respectively.

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INTRODUCTION

Energy is vital for our relations with the environment, and thus the research to resolve problems related to energy is quite significant since life is directly affected by energy and its consumption. Fossil fuel based energy resources still predominate with the highest share in global energy consumption (Chinumol and Victor, 2015). Desert encroachment and global warming are few among many resultant effects. Most urban dwellers also use kerosene and other petroleum by products for cooking amidst its attendant environmental hazards. Fossil fuels are not environmentally friendly owing to emissions arising from by products of combustion which constitute health hazards (Basil, 2013). The energy required for cooking is supplied by non-commercial fuels like firewood, agricultural waste, cow dung and kerosene (Abdulhamid, 2017).

Nigeria is blessed with a significant level of solar insolation. The country receives about 5.08×10^{12} KWh of energy per day from the sun (Aremu and Akinoso, 2013). The technology of solar cooking involves the conversion of solar

energy to heat energy. The heat is then directed to cooking pot for food preparation. Solar cooking systems could be box type, concentrating type or a hybrid of the two. Box-type solar cooker makes use of both diffuse and direct radiation while the concentrating type depends on its ability to make use of direct radiation only (Aremu and Akinoso, 2013). Cooking is the art, technology and craft of preparing food for consumption with the use of heat. Cooking techniques and ingredients vary widely across the world, from grilling food over an open fire to using electric stoves, to baking in various types of ovens, reflecting unique environmental, economic and cultural traditions and trends (SC, 2016). Solar cookers are heat exchangers designed to use solar energy in cooking process (Haftom *et al.*, 2014). In supplying the needed energy, solar cookers can fully or partially replace the use of firewood for cooking in many developing countries (Haftom *et al.*, 2014). Solar cooking is the simplest, safest, most convenient way to cook food without consuming fuel or heating up kitchen. Many people choose to solar cook for these reasons. But for hundreds of millions of people around the

world who cook over fires fuelled by wood or dung, and who walk miles to collect fire wood or spend much of their meagre income on fuel, solar cooking is more than a choice-It is a blessing (SC, 2016).

About two billion people are daily dependent on firewood as a source of their domestic and heating energy. They live in the tropics which are the most favourable area for harnessing solar energy (Haftom et al., 2014). As the solar energy intercepted by the earth in one year is ten times greater than the total fossil resources including undiscovered and unexplored non-recoverable reserves (Medugu et al., 2013). It is expected that the present worldwide research and development program on solar energy will help to solve the future energy crisis of the world (Medugu et al., 2013).

SOLAR COOKERS AND THEIR TYPES

Solar cookers are devices that cook food using only solar radiation and can save conventional fuels to a significant amount. It is the simplest,

safest, most convenient way to cook food without consuming fuels or heating up the kitchen (Mohammed, 2015). Several factors including access to materials, availability of traditional cooking fuels, climate, food preferences, and technical capabilities affect people's perception of solar cooking (Ismail and Isah, 2013).

Types of Solar Cookers

There are three types of solar cookers:

1. Panel Solar Cooker
2. Box Solar Cooker
3. Parabolic Solar Cooker

Panel Solar Cooker

Figure 1 is the pictorial view of a panel solar cooker. The panel cooker is the least expensive type of solar cooker. It is designed to reflect sunlight over the entire surface of a lightweight. Cooking pot is said to be coated with black colour on the outside with non-toxic paint. They are unstable in high winds and do not retain as much heat when the sun is hidden behind the clouds (SCP, 2015)



Fig.1. Panel Solar Cooker (SCP, 2015)

Box Solar Cooker

Figure 2 is the pictorial view of a box solar cooker. Solar box cookers (sometimes called solar ovens) are the most common and inexpensive type of solar cookers. This type of solar cooker consists of an insulated box made of cardboard, wood, metal or plastic. It is painted black on the inside and has a

large glass or Plexiglas window on top to let in sunlight. Just like panel cookers, box cookers can be left unattended in the sun for hours to cook food and pasteurize water. There is no danger of burning the food. Box solar cookers only need a slight adjustment to track the sun every few hours. Some solar box cookers have aluminium reflectors on the outside to

direct even more sunlight into the box (SCP, 2015).

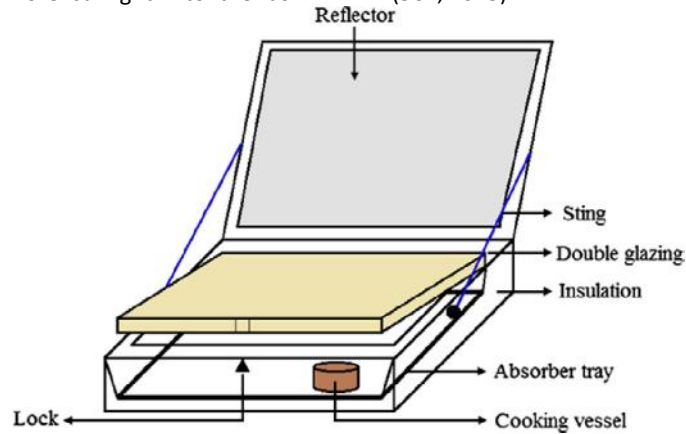


Fig.2. Box Solar Cooker

Parabolic Solar Cooker

Figure 3 is the pictorial view of a parabolic solar cooker. Parabolic solar cookers operate at a much higher temperature than panel and box cookers. They focus a narrow beam of sunlight on

to the bottom of a cooking pot that sits on a metal stand. Although parabolic solar cookers require regular adjustments to track the movement of the sun, they can be used from sunrise to sunset (SCP, 2015).

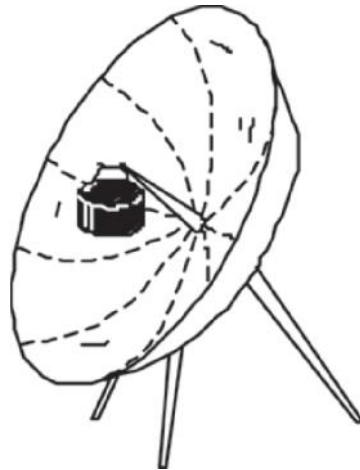


Fig. 3. Parabolic Solar Cooker (SCP, 2015)

Working Principles of Solar Cookers

Sunlight to heat conversion occurs when photons (particles of light) moves around in a substances. 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. The activity generates heat (SCP, 2015).

Advantages of Solar Cookers

The biggest advantage of solar cookers is eco-friendliness. By using one, dependency on gas or electricity can be gone. Better air quality indoors can be maintained, reduce carbon monoxide emission, enjoy cooler temperatures



indoors and conserve more fuel by reducing the need for air conditioning. Solar cookers are free, once you have the cooker itself. To operate one, all that is needed is sunlight; significant amount of money can be saved over a long term. As a result, solar cookers are being used increasingly in different parts of the world, especially in poorer communities with limited access to fuel and power since it is very simple to build one from scratch (Abdulhamid, 2017).

Research Objective

The objective of this research is to construct and carry out performance evaluation of the solar box cooker.

Energy analysis of solar cooker

Collector performance

In the evaluation of the collector performance, the following simplified energy balance equation can be used (Dasin, 2013):

$$Q_u = (F_t I_a - U_l(T_m - T_a))A_s = M_w C_p (T_b - T_a) \quad (3.13)$$

Where:

Q_u = Rate of useful heat energy extracted from the collector in (W)

F_t = Product of the transmissivity of the glazing and the absorptivity of the absorber plate

I_a = Average solar radiation (W/m^2)

M_w = Mass flow rate (Kg)

U_l = Solar collector overall heat loss coefficient in (W/m^2K)

T_a = Ambient temperature in ($^{\circ}C$)

T_m = Mean temperature ($^{\circ}C$)

T_b = Boiling point of water temperature ($^{\circ}C$)

The mean temperature of air can be estimated through the relation Lecuona et al. (2013)

$$T_m = \frac{T_a + T_b}{2} \quad (3.14)$$

Collector Efficiency

Collector efficiency is defined as the ratio of the rate of useful thermal energy leaving the collector to the

useable solar irradiance falling on the collector area (Fabio, 2008):

$$\eta_c = \frac{Q_u}{A_s I_a} \quad (3.15)$$

Thermal efficiency

The overall thermal efficiency of a solar cooker can be calculated from the following equation given by Elamin and Abdallah (2015) as:

$$\eta_{u} = \frac{M \Delta T}{I_a A_s \Delta t} \quad (3.16)$$

η_{u} = Overall thermal efficiency

M = Mass of the water

ΔT = Difference between the maximum and ambient air temperature

I_{av} = Average solar intensity (W/m^2) during the time interval

A_{sc} = Surface collector area of the cooker

Δt = Time required to achieve the maximum temperature of the cooking vessel

Collector Dimensions

3.5.4.1 Solar cooker surface collector area

The surface collector area A_s of box solar cooker is from the following equation given by Ekechukwu and Abdussalam (2001) as:

$$A_s = \frac{M C_p \Delta}{I_a \tau \eta} \quad (3.17)$$

Where:

M_w = Mass of water to be boiled

C_p = Specific heat capacity of water at constant pressure

Δ = Change in temperature

I_a = Anticipated average total insolation (during the time, t)

η = Assumed overall cooker efficiency

t = Time desired for boiling of water in (sec)

Cooker Wall Insulation Thickness

The insulation thickness, x of the solar cooker wall is given from Fourier's law of conduction given by Ekechukwu (2001) as:

$$x = \frac{K A_s \Delta T}{q_l} \quad (3.18)$$

Where

K is the thermal conductivity of the insulator (fibre glass)



ΔT = change in temperature of absorber plate and that of ambient temperature
 q_L = Desired maximum rate of heat loss through the cooker walls (q_L = 7% of incident average solar radiation) by Ekechukwu and Abdussalam (2001).

Stagnation Temperature Test

Stagnation temperature test is an important parameter because it depicts the ability of a cooker develops and retains minimum temperature which in turn reflects on the quality of the design and performance. Therefore standardized stagnation temperature is given by Ashok and Sudhir (2009) as:

$$S_s = 700 \left(\frac{T_s - T_a}{I_a} \right) \quad (3.19)$$

Where:

S_s = standard stagnation test

T_s = Maximum surface temperature

T_a = Ambient temperature

$$T_s = \left(\frac{7M}{\sigma} \right)^{1/4} \quad (3.20)$$

T_s = Theoretical maximum surface temperature ($^{\circ}\text{C}$)

M_w = is the mass of water in the cooking vessels (Kg)

σ = Stephen – Boltzman constant ($\text{Wm}^{-2}\text{K}^{-4}$)

MATERIALS AND METHODS

Materials Selection

i. **Reflectors:** In selecting the reflector for the solar cooker, plane reflector was used due to its high reflectance and low cost. Each reflector was attached to ply wood frame to hold the reflector in place.

ii. **Outer and inner casing:** Materials for casing includes; aluminium, fibre sheet, wood and galvanized iron. These materials have very well weather stability as well as durability, but differ in cost and weight. Ply wood was selected due to its; Low heat conductivity, Surface dimensional stability, High strength to weight ratio, Chemical resistance.

iii. **Glazing:** Glass and plastics are materials that were used in glazing. Transparent glass was selected due to its; material strength, durability, non-degradability when exposed to UV light and provision of heating through green house effect.

Glazing performs the following functions (Lefthriotis and Yianoulis, 2012):

- i. Serves as a shield to the absorber plate from outside the environment.
- ii. Minimize heat loss by convection and radiation from the absorber plates
- iii. Transmit direct and diffuse solar radiation to the absorber plate with minimum loss.

Other features of glazing are reflection(r), transmission (T) and absorption (α)

The purpose of using glass cover is because it is highly effective in reducing heat loss from the absorber plate. Also it can withstand high temperature than plastics.

iv. **Absorber plate (cooking chamber):** It absorbs both direct and diffuse solar radiation from the window frame. Aluminium plate was selected due to its good thermal conductivity, durability, appearance, corrosion resistance.

v. **Insulation:** Insulating material are used to minimize heat loss. Materials that are available are of different varieties. They include fiber glass, plywood, expanded polystyrene, cork and polyurethane form. Selection of one of the insulation material was based on cost, durability and its effectiveness. Material with low thermal conductivity was selected for better performance.

Fibre glass was used as insulating material due to the following advantages; Low heat conduction, Low density, Good mechanical strength, Resistance to fire.



Fig. 4. Constructed Solar Box Cooker

Measuring Equipment for Experimentation

The following measuring equipment were used:

i. Thermometer: This is a sensor for measuring temperature. This sensor consists of two dissimilar metal wires joined at one end and connected to a thermocouple thermometer or other thermocouple-capable device at the other end. When properly configured, thermocouple can provide temperature

measurements over wide range of temperatures (KM330 model).

ii. Weighing scale: Are device used in measuring weight (3D model STL-Finder).

iii. Solarimeter: is a pyranometer, a type of measuring device used to measure combined direct and diffuse solar radiations. Integrating solarimeter measures energy developed from solar radiation based on the absorption of heat by a black body (KIMO Solarimeter SL100-Kleinschm).

Table 1: Recommended Average Days for months and Values of n_i (Day of the Year) by months

Month	Date	n_i	Hours
January	17	17	384 – 408
February	16	47	1104 – 1128
March	16	75	1824 – 1848
April	15	105	2496 – 2520
May	15	135	3216 – 3240
June	11	162	3864 – 3888
July	17	198	4728 – 4752
August	16	228	5448 – 5472
September	15	258	6168 – 6192
October	15	288	6888 – 6912
November	14	318	7608 – 7632
December	10	344	8256 – 8280

Source: (Duffie and Beckman, 2013).

Experimental Set up

The system was setup as shown in figure 4, where the solar cooker was facing north-south. One end of each of the three thermocouples was attached to the glazing, levelling tray and pot. A pyranometer was placed on the collector

with its plane parallel to the plane of the collector. The small sized reflectors R1 and R2 were tilted at 45° and 15° respectively where the big sized reflector is fixed at 90° using the optimum collector slope for Zaria location (21°).

Table 2. Simulation parameters for solar box cooker model

Parameter	Value
Number of glazing	2
Extinction coefficient of glazing	0.037
Refractive index	1.526
Absorptivity	0.9
Reflectivity	0.9
Collector depth	0.4m

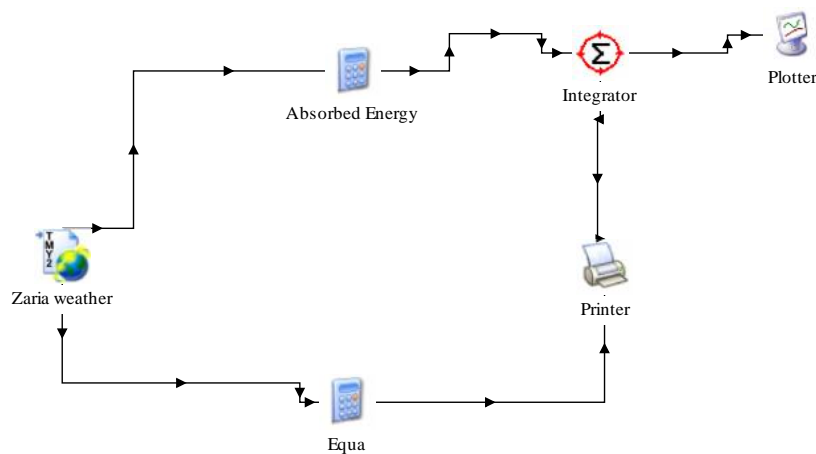


Fig. 5. TRNSYS Simulation Model

RESULTS AND DISCUSSIONS

The Variation of Solar Insolation with Time

Figure 6 shows the average solar radiation incident on surfaces at different time intervals for the 4 conservative days. The fluctuations indicate the effects of cloud cover after each 10 minutes to know the average intensity of the sun

from 10:00am to 2:00pm. The curve line is a regression line showing line of best fit for the co-efficient of determination (r^2) which was found to be 91.87% .

This is the curve; it shows the graph for the four days along with the polynomial curve for the average of the four days

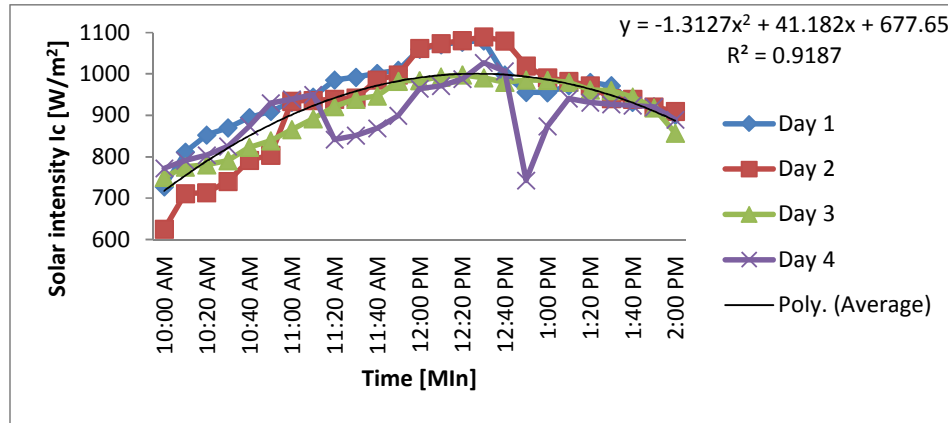


Fig. 6. Variation of Average Solar Intensity with time from 28/10/2016 to 31/10/2016

Design Month

Figure 7, shows solar radiation observer and presents the incident solar radiation on a horizontal surface and ambient temperature on 16th August (5448-5472hrs) in Zaria. It can be observed that there is steady increase in

solar radiation intensity from 12 noon (5460hrs) until it reaches its peak at about 2 p.m. (5462hrs), from then it decreases gradually till 8p.m (5468hrs) when the sun sets. The solar oven model was simulated within this time interval (12noon-2:00p.m).

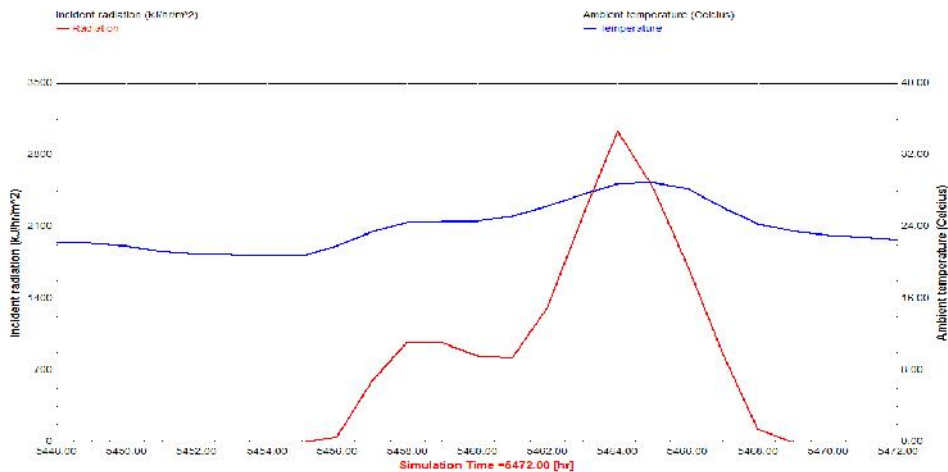


Fig. 7. Solar radiation and ambient temperature variation for 16th August for Zaria.

Source: (Mohammed, 2015)

Variations of Simulated and Experimental Collector Efficiency

Figure 8 shows the variation of simulated and experimental collector efficiency. From the figure, it was found that both the simulated and the

experimental results follow the same trends. And also using excels software, the co-efficient of determination (r^2) for both the simulated and experimental results were found to be 98.8% and 94.1% respectively.

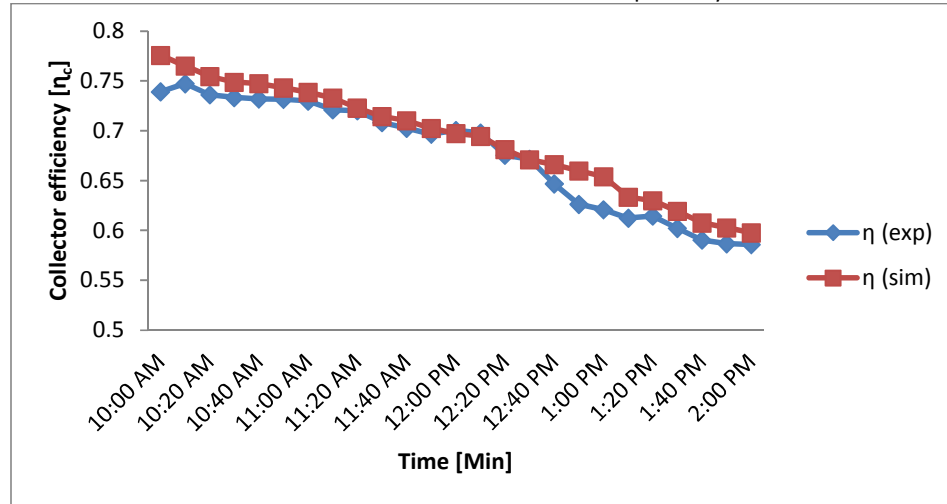


Fig. 8. Variation of efficiency on the collector surface over time difference for simulation and experimental results.

Comparison of Simulated and Experimental Results

Figure 9 shows the variation of experimental and simulated results of solar radiations from 10am-2pm for 28th October, 2016. From the figure, the experimental solar radiation rises from 710 W/m² at around 10:10am gradually and reaches 11:10am. Were at 11:10am,

there was rapid increase due to the clarity of the sky which leads to high solar radiation. It reaches its peak value at 12:30pm. From then, the radiation was dropping up to 2pm. And from the figure below, both the simulation and the experimental value follows the same trend.

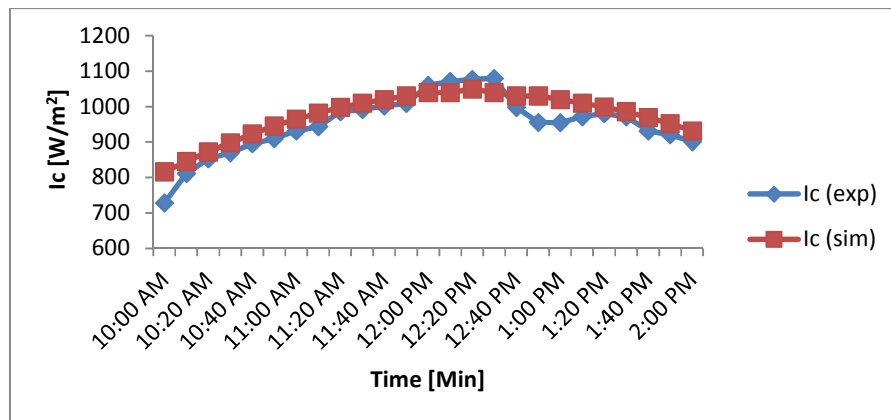


Fig. 9. Experimental and simulated incident solar radiation with local time (28th October, 2016)

Figure 10 below is a graph of experimental and simulation stagnation temperature readings against time. From the figure 10, it can be seen that at 10:00am, the experimental stagnation temperature is around 64°C. Then at 10:10am that is after 10minutes, it increases to around 70°C. The increment in temperature was due the availability of the solar radiations during the day. Also, it can be seen that 10:20am, the stagnation temperature then increases to around 76°C. This shows that from 10:10am to 10:20am, the increase in

stagnation temperature is 7°C. That was how the stagnation temperature increases continuously with time up to 1:00pm. At 1:00pm to 1:20pm the temperature was around 137°C the stagnation temperature was constant at this time interval due to the intermittent cloud cover. And there wasn't drop in temperature due to good insulation in the solar cooker. The Stagnation temperature was around 143°C at 1:30pm. Then after 10minutes, the stagnation temperature drops to around 138°C due to low solar radiation at that moment.

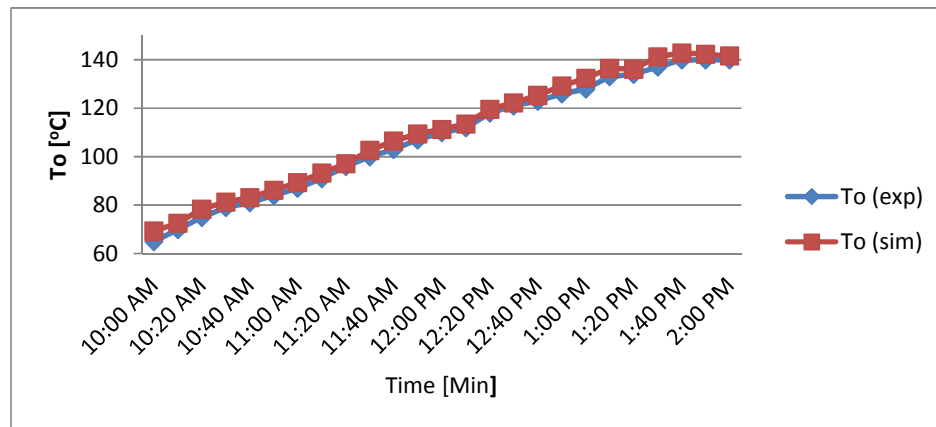


Fig. 10. Experimental and simulated stagnation temperature with local time (28th October, 2016)

Figure 10 is a graph of experimental and simulation results for ambient temperature for 28th October, 2016. From the figure, it can be seen that at 10:00am, the ambient temperature in the morning was around 28°C. After 10minutes, that is at 10:10am, the ambient temperature increases to around 29°C due to clarity of the sky. At 10:10am to 10:20am, the ambient temperature was constant due to the effect of cloud. Also, at 10:20am to 10:30am, the ambient temperature increases to around 30°C due to clarity of the sky. Then, from 10:30am to 10:40am, the ambient temperature was constant due to the intermittent cloud cover. From 10:40am to 10:50am, the ambient temperature increased to around 32°C. This was due to high solar intensity. The ambient

temperature reaches its peak value at 11:30am to 12:10pm were the temperature was at 35°C at higher solar radiation. Then from 12:10pm to 12:20pm, the ambient temperature drops to 31°C due to the intermittent cloud cover. The temperature is also constant from 12:20pm to 12:30pm due to cloudy effect. All the fluctuations that occurred were due to cloudy effects. And the readings stops at 2:00pm were the ambient temperature is at 35°C.

CONCLUSIONS

This is to conclude that using three reflectors for solar box cooker under Zaria metrological condition aid in boosting solar radiations into the cooking chamber which results to heat gain. Also from the graphs that were plotted, the simulation



and the experimental results were conformed with each other which show that high solar radiation during the day for the month of October is always from 1PM to 2PM. Then from 2PM, solar radiation always tends to start decreasing. This is to say when ever solar cooker is to be used during the day time, it must be placed under the sun before 1PM to enable the solar collector in the cooking chamber to gain high amount of solar energy for cooking food items.

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