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Development and Preliminary Performance Evaluation of a Multi-source Powered Drying Oven

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Abstract. For both rural and urban utilization as deemed fit, a multi-source powered oven dryer for drying of perishable foods and agricultural products was developed in this study. Three different heat sources are incorporated into this design. The heat generation sources are electricity, charcoal and gas. The heating element, the charcoal compartment, and the gas compartment are manually interchangeable for maximum utilization. The capacity of the chamber is 900 cm^2 with three sets of trays for drying food. The oven was lagged using fiber glass to ensure good insulation and prevent high energy loss due to heat conduction. During testing, the chamber temperature of 103ºC, 105ºC, and 120ºC were reached for electricity, charcoal and gas, respectively; when drying the cassava chaff at different masses (15, 30, and 45 g). The results revealed that the time of drying increases, the weight loss increases and the moisture content inherent in the cassava chaff reduces. However, the gas heat source gave a fast drying as a result of the high heat generated compared to other sources. This design is preliminary tested to work satisfactorily using the three different heat sources. Further test would be carried out on other agricultural products and the drying process would be optimized. The drying kinetics of the products would also be studied. This design is fit for purpose as either of the sources of heat can be used with respect to availability, it is significant as it can be employed in both the urban and in rural areas.

INTRODUCTION

Drying is very essential in preserving food items and agricultural products for future usage [1]. An oven or dryer is a thermally insulated system which is utilized in heating, baking, or drying a substance [2, 3]. These substances could be perishable goods, agricultural produce, and consumable materials. Most ovens designed are majorly powered by a single energy source. However, modern ovens have been designed to combine at least two different energy sources for drying, baking, and roasting [4].

Harvested farm products are liable to be wasted as a result of poor infrastructure in preserving them. With the several methods of food and agricultural product preservation, the bulk percentage is taken by drying [1]. Drying helps in the reduction of moisture content from the substance to be dried for improved shelf-life through the prevention of bacterial growth.

Although the utilization of solar energy, which is dependent on weather conditions, is a traditional drying technique known to be the most economical technique [1, 5]; the drying process has no controlled parameters. Hence, the qualities of drying and time loss are inevitable [6, 7]. Convective method of drying applies hot air under atmospheric pressure in drying of the products. In this method, there is heat and mass transfer between the hot air and products to be dried. Tray drying system are utilized in drying due to heat conduction technique. The product to be dried is situated

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on a tray in the oven and with the passage of hot air on the product in the tray. This process allows the heat from the hot-air to flow towards the product to be dried as a result of difference in temperature. This leads to evaporation of moisture from the product and consequent drying of the products [7 – 9].

A common occurrence in developing nations is the irregular supply of electricity. Nigeria, the most populous African nations, till date suffers from this occurrence of epileptic power supply. As a matter of facts, it is practically difficult in finishing what one starts with an electrical device. There is disparity between the population growth of developing countries and their food production. The population growth is more than food production. Therefore, most of the populace are known to feed on available cheap and starch-based foods because of their affordability. Perishable products cannot be easily stored in their basic form especially in rural areas or farm settlements. Hence, it is very expedient to design a multi-source powered oven for drying various products such as agricultural products (cassava chips, plantain chips, starch, pepper, and so on), forage crops for animal feeding, and so on. Researchers have developed different dryers or oven that works on different heat sources including coal dryer, kerosene dryer, electric dryer and gas-fired dryer [10 – 13]. Even dryers using dual heat sources have been developed [14]

This study develops a novel drying oven that is capable of utilizing three different heating sources for the removal of moisture as well as drying various agricultural products. A brief performance evaluation of the dryer was done to compare the drying rate of each of the heat sourced used.

METHODOLOGY

Material Selection

The design of the multi-powered drying oven took a number of elements into account. The following elements were taken into account: ease of part assembly; oven size; drying influence on the environment; heating temperature; spacing between separate trays; drying duration; and the size and geometry of the drying chamber.

The material selection criteria (Table 1) were based on the differential features found in various types of iron available in the area. Durability, workability, high thermal resistivity, corrosion resistance, high creep resistance, and malleability are some of the properties taken into account.

TABLE 1. Material Selection

S/N	Oven component	Functions	Reason for selection
1.	Mild steel	For the external part (bodywork) of the oven	Availability and low cost
2.	Stainless steel	For the internal walls of the drying oven	Availability and suitability
3.	Metal pipes	For the framework (edges) of the oven	Availability and suitability
4.	Rockwool/fiber glass	For lagging or thermal insulation of the drying oven	Availability and suitability
5.	Three pin plugs	For the completion of the electrical circuit to a socket	Availability
6.	Mini brazier	For the containment and burning of charcoal	Suitability
7.	Gas burner	For burning the hydrocarbon gas in heating the drying container	Suitability
8.	Heating element	Converts electrical energy into heat energy required for drying processes	Availability and suitability
9.	Gas hose	Connects the gas burner to the external gas cylinder	Resistivity to breakage and leakage
10.	Gas valve control	Attached to the gas burner for adjustment of gas flow rate	For ease of control
11.	Camping gas pressure regulator	Serves as a link regulating the pressure of gas from the tank to the burner	Pressure control and safety

The goal of employing local materials in the drying oven's construction was to create a near enough replica at a reasonable cost and with alternate heat sources. The drying oven was made up of three different heat sources; gas, charcoal, and electric; which are manually interchangeable. Fig. 1 shows the isometric and orthographic projection of the drying oven. The exploded view, Fig. 2, shows the various components that make up the multi-source powered oven and their dimensions for better understanding.

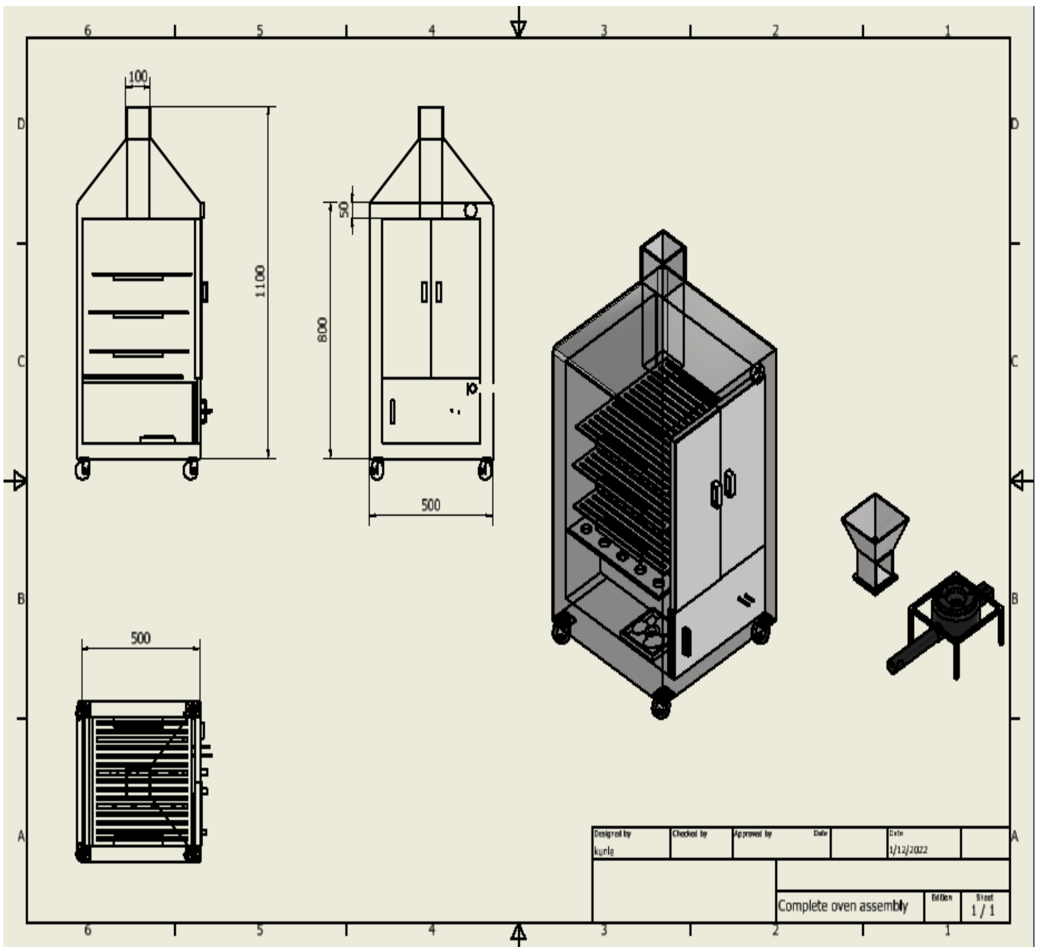

FIGURE 1. Isometric and orthographic projection of the multi-source powered oven

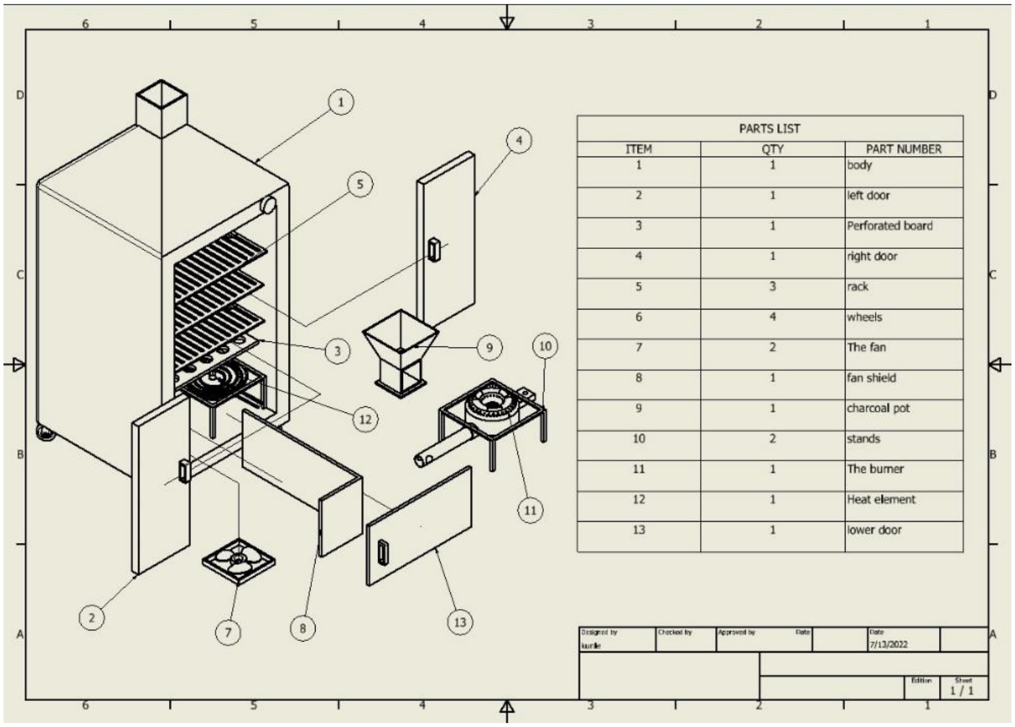

FIGURE 2. Exploded view of the drying oven

Design Description

According to the conceptual design, the gas oven was built using indigenous materials. The oven comprises of housing unit (frame), oven door, tray, gas regulator, oven-firing door, heating gas burner, perforated plate, chimney and thermocouple. The dimension of the outer layer (body) of the device is $500 \times 500 \times 800$ mm using 1 mm thickness of mild steel. Mild steel (1 mm thickness) was used in making the inner layer of the device. The dimension of the inner layer is $400 \times 400 \times 700$ mm. The lagging material (insulator) used is fiber glass having a 50 mm thickness. This material was inserted as a thermal insulator to reduce heat loss between the inner and the outer layers. Fiberglass is noted for its lightweight, excellent strength, and thermal shock resistance.

There are two door chambers in the oven. The upper door chamber of the oven was made of mild steel, and 50 mm thick fiber glass was placed between the steel plate to prevent heat loss through the door. The energy sources compartment is housed in the chamber at the bottom. Inside the oven firing door is a detachable shield made of mild steel with dimensions of $400 \times 150 \times 200$ (length, breadth, and height accordingly) in mm for the fan when the electrical source is turned on, the stands on which the electrical element and burner has a height of 170 mm. The oven gas burner is a perforated O-shaped pipe having small openings at intervals. For escape of heat, the perforations are made just below the burner. Heat energy escapes through holes produced directly beneath the burner and circulates throughout the oven chamber. The power of the heating element was rated 1000 W, while the charcoal is placed in a charcoal pot that can hold up to 1 kg of charcoal. To prevent direct flame from reaching the inner chamber from the heat sources, a deflector plate $(400 \times 400 \times 1)\ mm$ was used at the base of the chamber and set at a height of 240 mm for uniform heat distribution. For the mobility of the oven, carrier handles are attached to the sides of the oven. At the top of the oven, a chimney was made for energy balance in the chamber.

The oven drying chamber comprises of three trays dimensioned 400×400 mm, with welded galvanized wire mesh (Fig. 3).

Figure 3. Fabricated multi-source powered oven

Design Calculations

The formula considered in the evaluation of the performance of the drying oven include the following;

1. Heat loss through the walls of the oven
2. The heating element rating
3. Design analysis for the mass of drying chamber
4. The quantity of heat required
5. Thermal efficiency

Total Heat Loss through the Walls of the Oven

The formula used to calculate heat loss by conduction [15] is given as Equation (1).

$$Q = \frac{K_A\, A\,(T_1 - T_2)}{L_A} = \frac{K_B B\,(T_2 - T_3)}{L_B} = \frac{K_C\, C\,(T_3 - T_4)}{L_C} \tag{1}$$

where L_A L_B L_C = Thickness of walls (m), K_A K_B K_C = Thermal conductivity of the walls (W/mK), T_1, T_4 = Temperature of the wall surface (^oC), T_2, T_3 = Temperature of the interfaces 2 and 3 respectively (^oC)

Total Heat Loss through Convection on the Outer Surface of the Wall

The formula (Equation 2) used to calculate heat loss through convection on the outer surface of the wall [15].

$$Q = hA\Delta T = hA(T_S - T_\infty) \tag{2}$$

where T_S = Temperature of the surface (30^oC), T_∞ = Room temperature (28^oC), T_F = Film temperature
The average heat transfer coefficient was determined using Equation (3).
Average heat transfer coefficient,

$$h = \frac{k}{L}(0.677(pr)^{\frac{1}{2}} \times (0.952 + pr)^{-\frac{1}{4}} \times (Gr)^{\frac{1}{4}}) \tag{3}$$

where Pr = randtl number = 0.72848, Gr = Grashoff number

The average heat transfer coefficient was calculated to be 1.7482 W/m^2. ^{o}C
Heat loss through convection = 1.7482 × 0.4 × 2 = 1.39856 W
This is the amount of heat loss by convection on the outer through one wall. For the four lagged walls the amount of heat loss by convection on the outer walls would be 5.59424 W.

For Electricity

Equations (4) – (6) were used to determine the total heat transfer rate between two solids.

$$Q = C_h(T_{h1} - T_{h2}) = C_c(T_{c2} - T_{c2}) \quad (4)$$

$$ln\,{}^{\theta_2}/_{\theta_1} = -UA\left[\frac{T_{h1}-T_{h2}}{Q} + \frac{T_{c1}-T_{c1}}{Q}\right] \quad (5)$$

$$\theta_m = \frac{\theta 2-\theta 1}{ln\,{}^{\theta_2}/_{\theta_1}} \quad (6)$$

where: Q – total rate of heat transfer, A – area of the material. C_b (specific heat capacity of substance (cassava)), 1450 J/Kg^{-1}K^{-1} and TRM (Oven room temperature, 28^{o}C = 301 K), Eq. (7).

$$\theta_m = \left[\frac{383 - 301}{ln\,\frac{383}{301}}\right] = 304.4K \quad (7)$$

Therefore, the logarithmic mean temperature difference between the solid at a temperature (T_h) and the outermost sheet metal temperature (T_c) separated by an insulator (rock wool) is 304.4K.
Heat required (Q_H) was calculated to be 1,498KJ using Equations (8) – (9).

$$Q_H = MC\theta \quad (8)$$

$$Q_H = M_b \times C_b \times TRM \quad (9)$$

where: Q_H – heat required, M_b – mass of the substance, C_b – specific heat capacity of substance, TRM – oven room temperature.

Determining the Capacity of Heating Element

The electric heating element power rating is evaluated using Equation (10).

$$P = Energy\,/\,Time \quad (10)$$

where: P - power
Based on the Equations (11 – 12), the power rating of the heating element should not be less than 0.4867 kW.

$$P = I \times V \quad (11)$$

$$P = I^2 \times R = \frac{V^2}{R} \quad (12)$$

where: P - power (W), I - current (A), V - voltage (V), R - electric resistance (Ω). Work done, or energy expended is given by, Equation (13).

$$W = I \times V \times t \quad (13)$$

where: t – time (s), V – voltage (V), I – current (A). The resistance of the heating element is 0.64 Ω, current is 1.56 A while the cable size is 2.5 mm^2.

For Charcoal

This refers to the amount of energy supplied by the fuel fed into the charcoal pot having a calorific value (cv) of 15.5 MJ kg^{-1}. The Feed Conversion Ratio (FCR) can be computed using the for Equation 14.

$$FCR = \frac{Q_n}{CV \times \eta_g} \quad (14)$$

Performance Evaluation of the Drying Oven

Weight Loss of Agricultural Product

The drying oven was put to test to determine its function-ability and effectiveness using cassava chaff. The drying oven was tested using the three different heat sources. The substance to be dried at different masses of (15, 30, and 45 g) was put in a crucible and placed in the oven. Four varying times were used, which include 15, 30, 45, and 60 min, as the soaking time for the drying. The weight of the substance to be dried was initially taken and the final weight after drying for the stipulated time was obtained.

The weight loss of the substance dried by produced by the oven (W) was given by Equation 15;

$$(W) = m_B - m_A \tag{15}$$

where m_B is mass of substance before drying and m_A is mass of substance after drying.

The performance of the multi-source oven was evaluated by using the device in drying agricultural products (cassava shaft) as well as perishable foods. The quantities of the cassava shaft before and after drying were evaluated using weighing balance and the moisture content of the cassava shaft was determined by Equation (16).

$$\text{Moisture content} = \frac{A-B}{A} \times 100 \tag{16}$$

where: A - weight of the cassava shaft before drying, B - weight of the cassava shaft after drying.

A thermocouple was used to monitor the temperature of the chamber of the oven while another thermocouple was used to monitor the external temperature of the body during the operation of the device. This is to determine the amount of heat loss and the effectiveness of the fibre glass insulation used. These temperatures are obtained with time.

RESULTS AND DISCUSSION

Weight Loss and Moisture Content Removal Analysis

The experimental results that were run for 1 h with interval of 15 min for each heat source at various weights of the cassava chaff (15, 30, and 45 g) are displayed in Figs. 4 – 6. These figures show the relationship between weight loss and time, and moisture content and time for the respective heat sources of charcoal, electricity, and gas. It can be observed that there is a direct relationship between the weight loss and time. As the time of drying increases, the amount of water content being removed in the substance increases; therefore, a significant weight loss was observed. The amount of heat energy supplied by the charcoal and electricity heat source cannot be compared with that of gas. This was evident in Figure 6 as the rate of water removal from the substance was much compared to the other two sources.

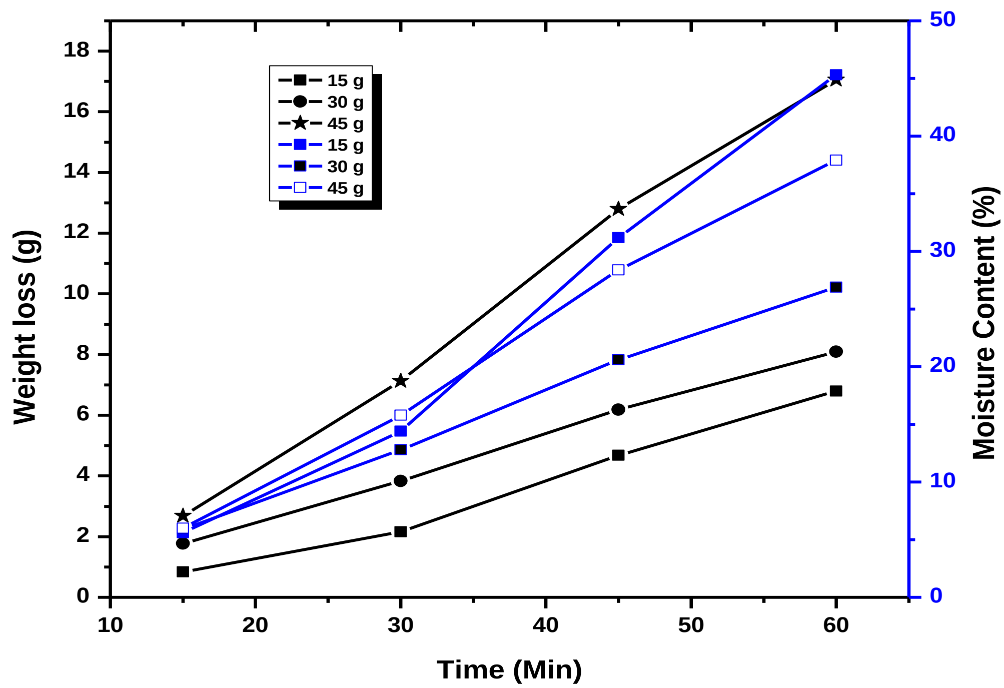

FIGURE 4. Weight loss and moisture content vs. time for charcoal heat source

In Fig. 4, the weight loss when 15 g mass of cassava chaff was used revealed an increase in the evaporation of the moisture present in the substance to be dried. The amount of moisture removed from the substance is significant to the percentage moisture content. The more the moisture removal, the better the percentage moisture content and the better the storage-ability and shelf-life of the product. It can be observed that the percentage moisture removal increases with time; however, no specified pattern was established in relation to the mass of the substance used unlike for weight loss. The smaller the quantity of substance, the faster the drying because more hot air is passed over the substance to be dried through heat and mass transfer which led to moisture removal from the substance being dried.

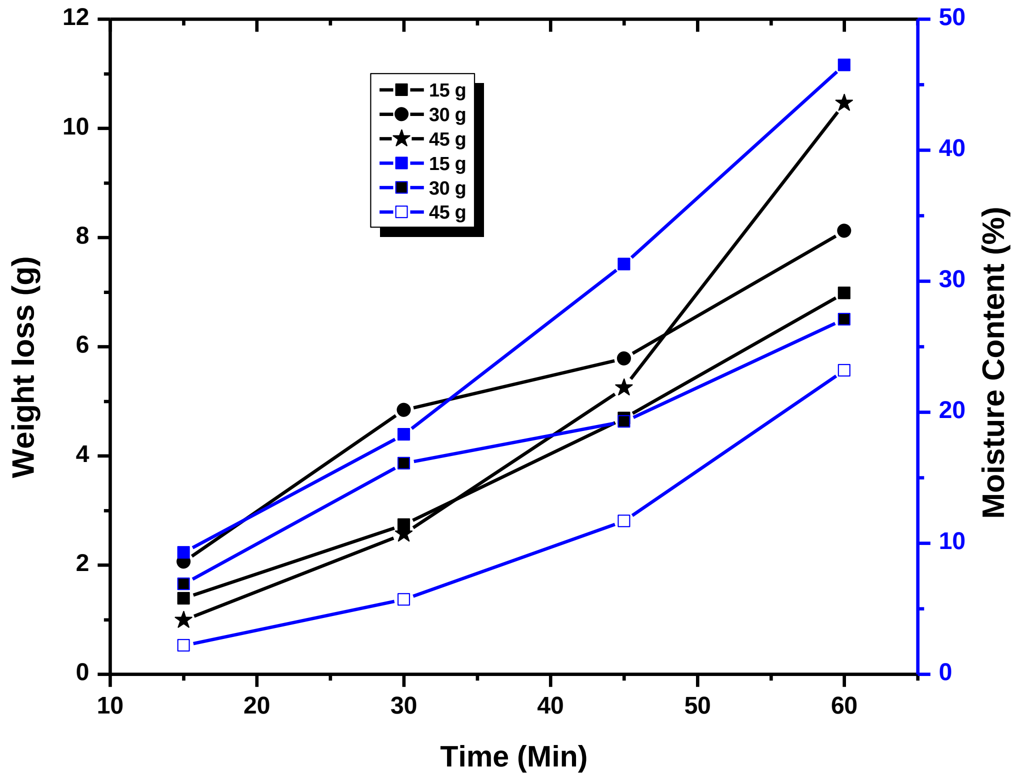

FIGURE 5. Weight loss and moisture content vs. time for electric powered source

A similar pattern of increase in weight loss with time was observed in Figs. 5 and 6. The amount of heat generated by the heating element via electricity supply was able to dry the cassava chaff. A pattern to show a direct link between the moisture removal from the substance and different masses of the substance was established. The more the amount of the substance, the more is the required time to dry the substance. The electricity powered oven when compared to the charcoal powered oven gave better increased weight loss as well as increased removal of moisture from the substance. This is possible owing to the presence of a fan to uniformly convey the heat generated in the oven chamber unlike when the charcoal was used. More so, the amount of energy generated by the gas is very high; hence, the quick nature of moisture removal and weight loss of the substance.

With proper monitoring of the charcoal powered oven, the performance of drying can be improved and could be utilized in rural areas. Although the performance of gas-powered oven for moisture removal is superb, the expensive nature of gas is a disadvantage to its usage especially for those in rural areas or farm settlements. Rural areas lacking electricity would find the utilization of the electric-powered oven challenging to employ. Hence, this design would find usage in urban area and in households that can afford any of the three heat sources.

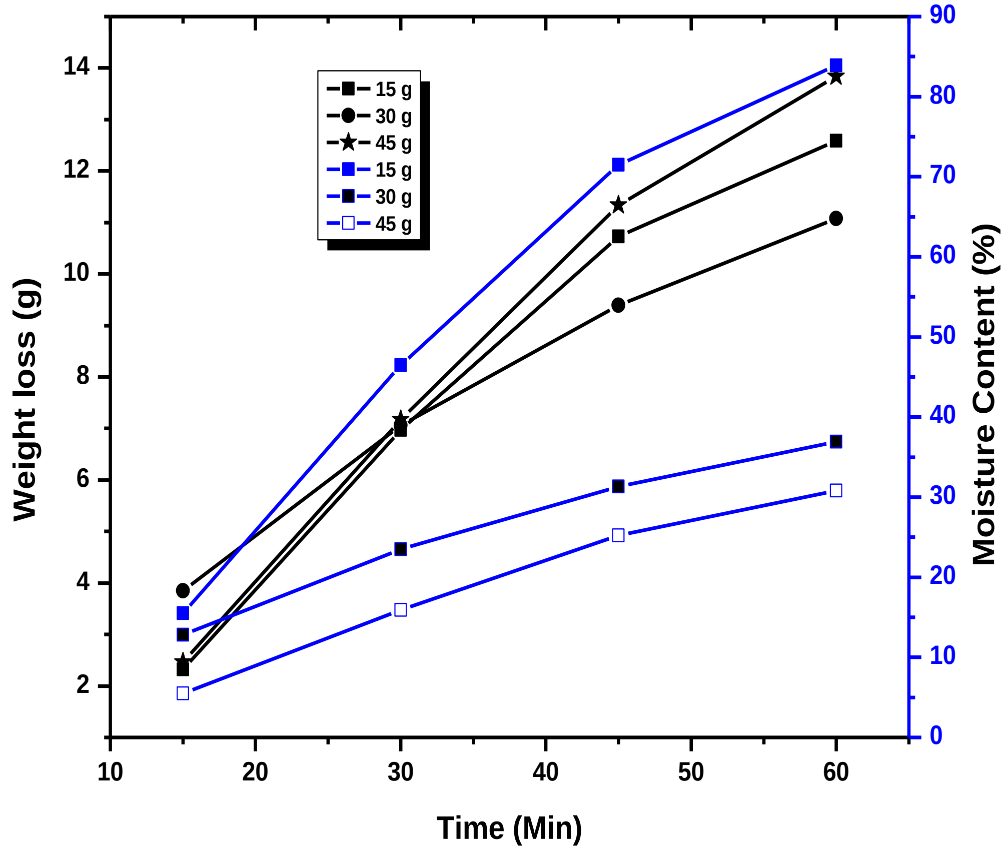

FIGURE 6. Weight loss and moisture content vs. time for gas heat source

Effectiveness of the Lagging

The amount of heat loss during the utilization of the three heat sources was found to be low (Fig. 7). The conduction of heat to the external body of the device from the inner chamber was found to be below 40ºC irrespective of the heat source used. This implies that the lagging material used in this design was able to hinder the unnecessary flow of heat energy off the device; thereby, reducing the accurate functionality of the device. As observed in Fig. 7, the gas heat source gave the highest inner chamber temperature. This is in line with the earlier observation which invariably affects the increase weight loss with time. Both the inner chamber temperature and external body temperature increase with time.

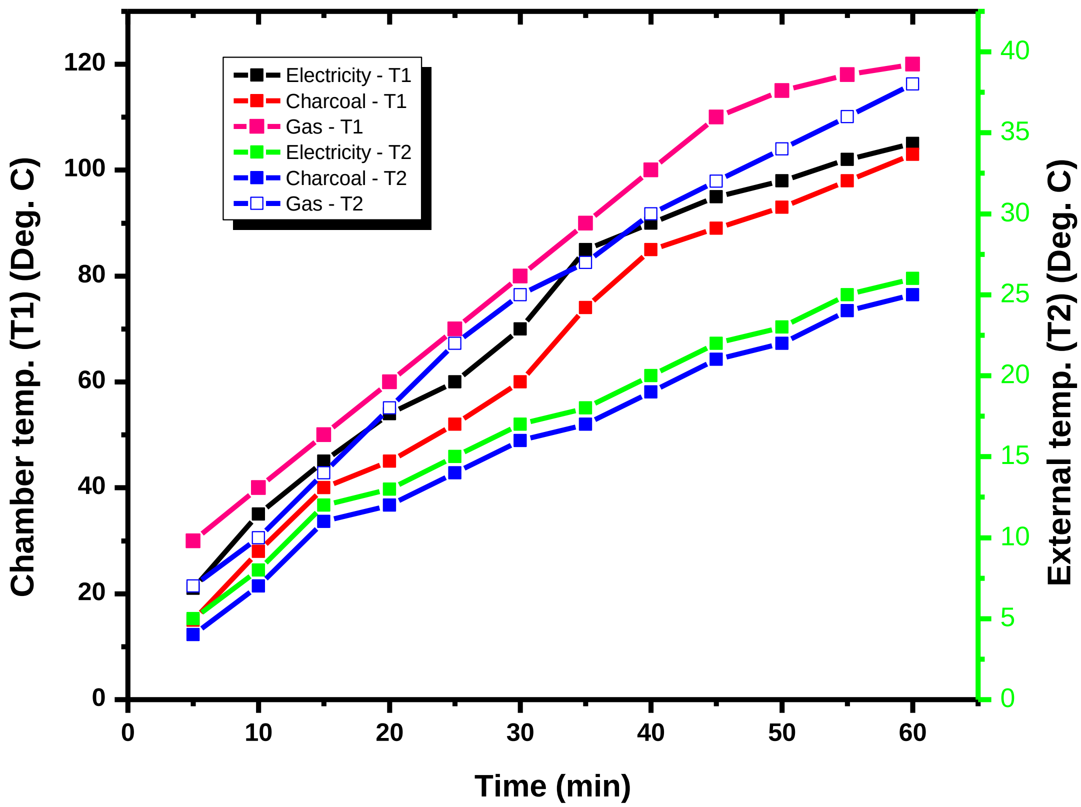

FIGURE 7. Chamber temperature and external temperature vs. time for different heat source

CONCLUSION

In this study, a multi-powered drying oven was developed and preliminarily tested to ascertain the functionality of the device. All the heat sources were effective in reducing moisture as well as drying the cassava chaff place in the oven. However, the rate of moisture removal from the substance was fastest when the gas heat source was used due to high heat energy generated compared to the electric and charcoal heat sources. The primary benefit of the gas heat source is that, unlike an electric element or the ignition of charcoal, does not require preheating or depend on power from an electric source sensitive to voltage fluctuations before cooking. As a result, it is better at a wider range of drying processes. However, it is costly and non-economical for rural users. Rural and urban dwellers will find this device useful as it gives them the opportunity to select any heat source at their convenience. The study recommends that further evaluation should be carried out on the drying oven using different agricultural products. The device should be optimized and drying kinetics of each product dried in it should be studied. More so, a bigger version of the oven is recommended to be developed for drying large quantity of food products.

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