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DESIGN AND CHARACTERIZATION OF A GAS-POWERED BAKING OVEN FABRICATED WITH LOCAL ENGINEERING MATERIALS

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ABSTRACT: Statistically, there is a high dependence on snacks in Nigeria for everyday food. This has made the production of snacks a lucrative venture in Nigeria thereby putting enormous pressure on the technological innovation of snacks production. A baking oven which is a thermally insulated cavity is the most widely used appliance in the food service industry, snacks inclusive. However, most ovens used in Nigeria for snacks production at the small/cottage industrial level are usually limited in one way or the other, hence this work. In this work, an oven with a capacity to bake 100 loaves of bread each weighing 200g was designed. The oven has a dual heating source with a top and down heating grills that is powered using a domestic cooking gas. Its dimensions are (1800 x 600 x 600) mm for height, length and width. The oven had a see-through window and a heat sensor to monitor the progress of the food being baked and the temperature respectively, without necessarily opening the door during operation. The oven had the heating capacity of 19.4 KW and cooking energy efficiency (CEE) of 70.79%. The organoleptic properties of the breads baked in the oven showed that a bread with high sensory attributes can be baked with the developed oven as there was no significant difference between the bread baked with the oven and the control of similar recipe baked in a conventional oven. The oven was therefore found suitable and convenient for baking cookies at the level of small/cottage industries.

KEYWORDS: Design, Fabrication, Gas oven, Baking, Local engineering, Performance evaluation.

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INTRODUCTION

Statistically, there is a high dependence on snacks in Nigeria for everyday food as snacks amount to one-third of daily energy intake (Njike et al., 2016). This has made the production of snacks a lucrative venture in Nigeria thereby putting enormous pressure on the technological innovation of snacks production. An oven is a thermally insulated cavity used for the cooking/transformation of foods into edible products. It is the most widely used appliance in the snack food service industry (Ilesanmi & Akinnuli, 2019). In order to bake the products, ovens are usually powered by heat generating fuels such as gas, oil, charcoal, coal, etc. (Chukwuneke et al., 2018), as baking involves a complex simultaneous heat and mass transfer process (Ilesanmi & Akinnuli, 2019; Genitha et al., 2014; Purlis, 2012). The released available energy from these fuels is transferred to the products by means of convection although conduction and radiation also play a role (Tong & Lund, 1990; Ozilgen & Heil, 1994). The oven sets and maintains the proper conditions of heat flux, humidity, and temperature to carry out the baking process and the removal of moisture from the products (Ilesanmi & Akinnuli, 2019; Chukwuneke et al., 2018; Carvalho & Martins, 1993; Manley, 2011). Commercially, ovens are available in various configurations like electric ovens, micro-oven and wood ovens, etc. (Ilesanmi & Akinnuli, 2019).

Most ovens used at the level of small/cottage food industries in Nigeria are limited in one area or the other. For example, most ovens are operated in the traditional setting, such as the hearth oven which limits operations in speed, volume and convenience of snacks production at the cottage level. Moreover, the modern and imported ovens are too expensive to be acquired by the small/cottage industries. Therefore, the study of baking oven is important because it could lead to a more efficient process of baking favourable to energy efficiency and better product quality (Ilesanmi & Akinnuli, 2019; Fellows, 2000; Akinnuli & Olufemi, 2019; Therdthai et al., 2003).

Nowadays, most ovens used in Nigeria at the level of small, medium and cottage industries are fabricated locally, but they are still limited in one way or the other such as lack of see-through windows to monitor the progress of baking. This results in the incessant opening of the oven door to ascertain the level of baking thereby delaying the baking time due to the alteration of the temperature each time the door is opened and lack of temperature/heat sensor interface.

Considering these outlined limitations and the fact that analysis and optimization of baking process and equipment is necessary to minimize energy consumption (Therdthai et al., 2003), a design of an oven which will incorporate these desirable features (see-through window and heat sensor) will be a welcomed development. Therefore, this work chooses to design and develop an oven that will address the shortcomings of the available locally fabricated oven by introducing a see-through window and a heat/temperature sensor to monitor both the baking process and the temperature/heat progress respectively.

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MATERIAL AND METHOD

Design Bases

The machine was designed and developed based on the following considerations: the machine should be simple in construction; it should have simple adjustment; it should be made with locally available materials with simple technology; it should be easy to repair and maintain and the cost of the machine must be within the capacity of small, medium and cottage industries. The oven dimensions were considered based on the target output of 100 bread pans each capable of containing 200g of bread dough, with top and down burner grill for maximum heat output.

Considerations for Oven Configuration

Oven configuration was based on fuel powering ability and a direct heating from domestic heating sources, so a cuboids-shaped oven of length to width to height ratio 1:1:3 was conceptualized. And since the bread were to be baked by heat transferred from a direct heating source, composite wall that is made up of mild steel (internal and external walls) and glass fiber insulation was considered for the structure so as to reduce heat losses.

Dimension of Bread Pans

Bread pans measuring 110 mm x 80 mm x 40mm (0.11m x 0.08m x 0.04m) and made from aluminum metal were used to contain the bread dough during the performance evaluation of the oven. Thus, the bread pan occupies a space of about 0.0088m^2 on the oven floor.

Determination of Oven Size and Housing Cavity

The oven is to have four racks with each rack carrying 25 bread pans. Since each of the bread pan has a base area of 0.0088 m^2, therefore 25 units of such pans has a minimum base area of 25x0.0088m or 0.22m^2. 450mm (45cm or 0.45m) spacing was allowed in between the racks for optimum convective heat circulation, making the height of the oven 1800mm (180cm or 1.8m).

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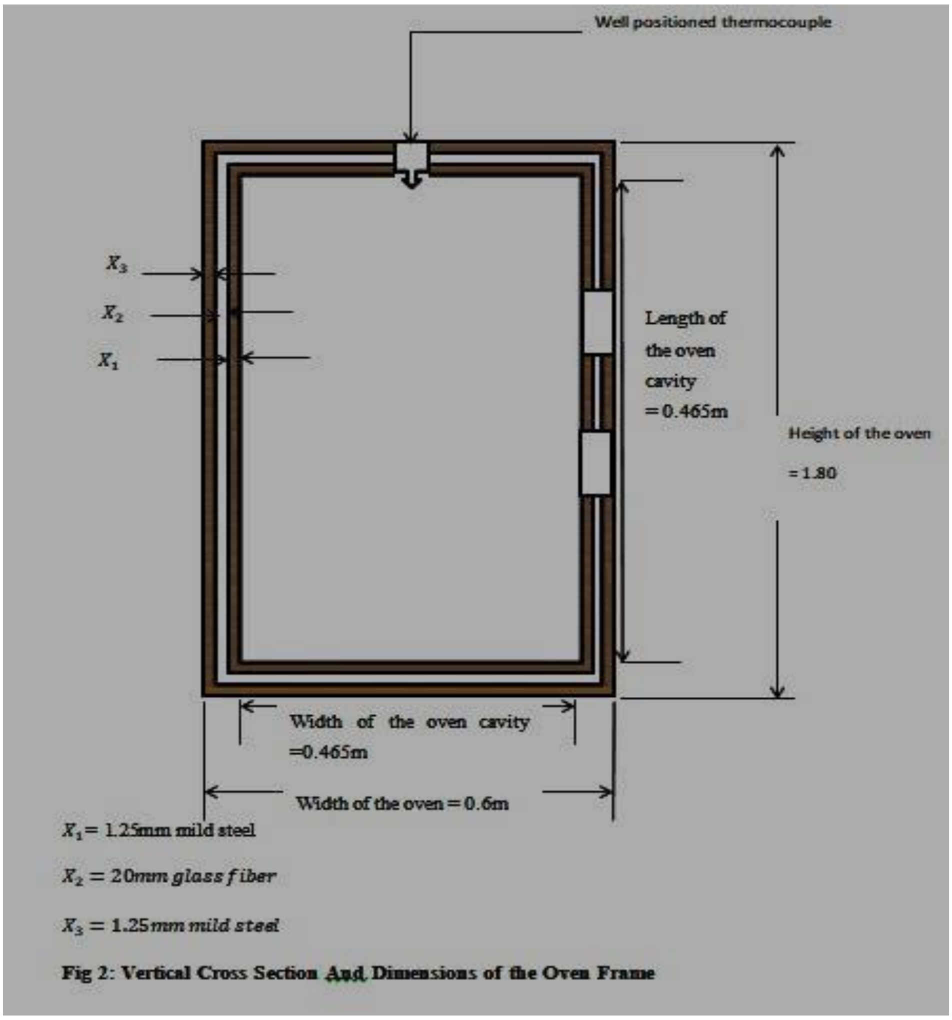

Fig. 1. Dimensional analysis of the Oven

Material Selection and Specifications of Oven Components

For the purpose of reducing costs and increasing local content, the oven was built with locally available engineering materials. The components of the oven are:

1. **Outermost oven wall:** The outermost oven wall was made from a plain mild steel sheet with the thickness of 1.25mm.
2. **Innermost oven wall:** The innermost oven wall was made from a mild steel sheet with thickness of 1.25mm.
3. **Base plate:** The oven base plate was made from a mild steel sheet with a thickness of 1.25mm.
4. **Glass fiber:** A space of about 20.0 mm was left between the innermost and outermost oven walls and was filled with glass fibre to help minimize heat losses from the inside oven wall during operation.

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5. **Baking rack:** A square baking rack with area $0.27m^2$ made of galvanized iron with a thickness of 10mm was used for loading of the bread in the oven (Zhou & Therdthai, 2008).

6. **See-through window:** A see-through window was inserted at the oven door. This is to enable the operator check the progress of the baking.

The dimensions and physical properties of the materials used for the construction of the direct heat oven is shown in Table 1.

Table 1: Dimensions and Physical Properties of Materials Used for the Oven Construction

Component	Material Used	Thickness & Plane Area of Material(m^2)	Volume (m^3)	Density of Mat. (kg/m^3)	Mass (kg)	C_P (KJ/kg℃)
Outer oven walls	Mild steel	$0.00125m^2$x$1.08m^2$	0.0013	7,833	10.59	0.60
Inner oven wall	Mild steel	$0.00125m^2$x$0.816m^2$	0.0014	7.833	10.96	0.60
Baking rack	Mild steel	0.001mx $0.00786m^2$	0.0005	7.833	3.916	0.80
Glass pane	Clear glass	0.02m x $1.08m^2$	0.0002	2.700	0.432	0.89
Entrapped	Air		0.0530	1.127	0.0597	0.0013
Outer oven walls	Mild steel	$0.00125m^2$x$1.08m^2$	0.0013	7,833	10.59	0.60

Specific heat capacity of materials and Density of air at 30℃ as obtained from Singh and Heldman (2001).

From Table 1, the total mass of oven components is:

$Mass_{total}$= Mass of Mild Steel + Mass of Glass+ Mass of Oven Air Cavity

M_T = 23.466+ 0.432+ 0.0597= 23.9577Kg

Selection of Heating Source for the Oven

Selection of heating source for the oven was based on the total sum of heat loads which includes the preheating of the oven, the baking of the bread, and heat losses during baking. It was observed from the total heat load that a direct heating source of domestic fuel (gas) with a grill heat power rating on the top burner 4.40kw (15000 BTU) and down burner 15.24kW (52000 BTU) was suitable for the oven.

Operating Conditions and Control of Heating Source to the Oven

Okafor (2014) showed that when the gas control knob of an adjustable gas burner is set appropriately, a steady rate of fuel combustion and heat supply is obtained. The gas oven was adjusted to deliver a steady heat supply at the non-luminous (blue colour) zone when operated indoors in a draught-free environment.

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Instrumentation and Control of the Oven

Control of heat supply into the oven was by means of the control knob on the burner grills located at the top and bottom base plates of the oven and the baking progress was monitored through the transparent see-through glass window on the oven door.

Design Factors for the Oven

From the data obtained from Table 1, an assumed temperature conditions of the oven and other constants, the following design factors were used for estimating the heating requirements of the oven:

Height of oven, H = 1.8m; length of the oven = 0.6m (out to out); width of the oven = 0.6m (out to out); length of the oven cavity = 0.465m; width of the oven cavity=0.465m; the total area of the oven cavity = 0.93m^2; inside oven cavity temperature, T = 220 °C; outside ambient (air) temperature, T ambient = 30°C; thermal conductivity of mild steel, k_1 = 50 W/(mK); thermal conductivity of glass fiber layer of insulation, k_2 =0.038 W/(mk); surface heat transfer coefficient at the inside of the oven wall, h_i = 27.8 W/(m^2 K); surface heat transfer coefficient at the outside of the oven wall h_o =5.7048W/(m^{2}k)

Estimation Of Heat Requirements for The Oven

The total heat load or requirement of the oven is given as

$$Heat_{total} = Heat_1 + Heat_2 + Heat_3$$

H_1: $H_{Preheat}$ is the quantity of heat required to preheat the oven from ambient temperature (30^{O}C) to maximum target preheating temperature (220^{O}C).

H_2: H_{Baking} is the quantity of heat required to bake 100 units of bread dough.

H_3: H_{loss} is the quantity of heat losses from the oven to the surrounding during operation.

Determination of Preheating Load ($H_{preheat}$)

The preheating requirement of the oven from its initial ambient temperature T_1 to target preheat temperature T_2 is given according to Singh and Heldman (2001) as:

$$H_{preheat} = MC_p\Delta T \qquad (1)$$

Where: M =mass of inside oven components (Kg); C_P=Specific heat capacity of inside oven components kJ/(kg℃); ΔT_{oven} = temperature difference between the ambient condition (30℃) and inside oven temperature (220℃).

The assumptions made over this preheating load estimation were:

1. A steady state heat transfer system;
2. An initial oven temperature of 30°Cas a datum prior to preheating and a target inside oven temperature of 220C;

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3. The hot oven cavity is isothermal with the inside oven wall during preheating; and an
4. Estimation of heat loads was computed at the upper limit of oven variables.

On these assumptions, the preheating load requirement of the oven was estimated by calculating the heat requirements of the various oven components undergoing heat changes from 30℃ to 220℃ (i.e. a temperature difference of 190℃).

According to Singh and Heldman (2001), the heat changes of the various oven components are obtained as:

$$\Delta H_{Oven\ component} H_1 = MC_P\Delta T_{steel} + MC_P\Delta T_{rack} + MC_P\Delta T_{glass} + MC_P\Delta T_{enclosed\ air} \quad (2)$$

$$\Delta H_{Oven\ component} = 5625.9KJ + 1140\ KJ + 140.5KJ = 6906.4J = 6.9064\text{kJ}$$

Estimation of Heat Requirement for Baking of the Bread

According to Paton (2013), the energy consumed in baking N units of bread is given by:

$$E_{bread} = N\left[M_{bi}C_{p_b}\left(T_f - T_i\right) + M_{bp}C_{P_{bp}}\left(T_f - T_i\right) + hfg_{100°\text{C}}M_{bi} - M_{bf}\right] \quad (3)$$

Where:

N =number of bread units baked; M_{bi} =initial mass of bread dough before baking (kg);

M_{bf} =Final mass of baked bread after baking (kg); CP_b= Specific heat capacity of bread dough (kJ/kg °C); (Obtained as a function of its proximate composition); M_{bp} =Mass of bread pan (kg)

CP_{bp} Specific heat capacity of bred pan kJ/(kg℃); T_i =Initial temperature of bread before baking at ambient temperature (°C); T_f =Final temperature reached by bread during baking (^{O}C) as read off a thermocouple; H_{gf100}= Latent heat of vaporization of water at 100°C (KJ/kg), (as obtained from steam tables); The Specific heat capacity of standard recipe bread was used

$$E_{bread} = N\left[M_{bi}C_{p_b}\left(T_f - T_i\right) + M_{bp}C_{P_{bp}}\left(T_f - T_i\right) + hfg_{100°\text{C}}M_{bi} - M_{bf}\right]$$

$$E_{bread} = 136.8kJ + 855kJ + 6840kJ = 7831.8KJ$$

Estimation of Heat Losses Through Oven Wall

The heat loss from the oven wall is given by Fourier's law of conductive heat transfer

Mathematically, the conductive heat transfer is written as:

$$Q = \frac{KA(\Delta T)}{dx} \quad (6)$$

Where: Q is conductive heat flow rate through the oven walls (W); K is the thermal conductivity of the wall materials ($W.m^{-1}.\ k^{-1}$); A is the cross-sectional area of the oven (m^2)

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dx is the thickness wall (m) for an oven made of three materials which are: internal wall (mild steel), external wall (mild steel) and insulator material between the internal and external walls (glass fiber)

For a composite body in series as shown below,

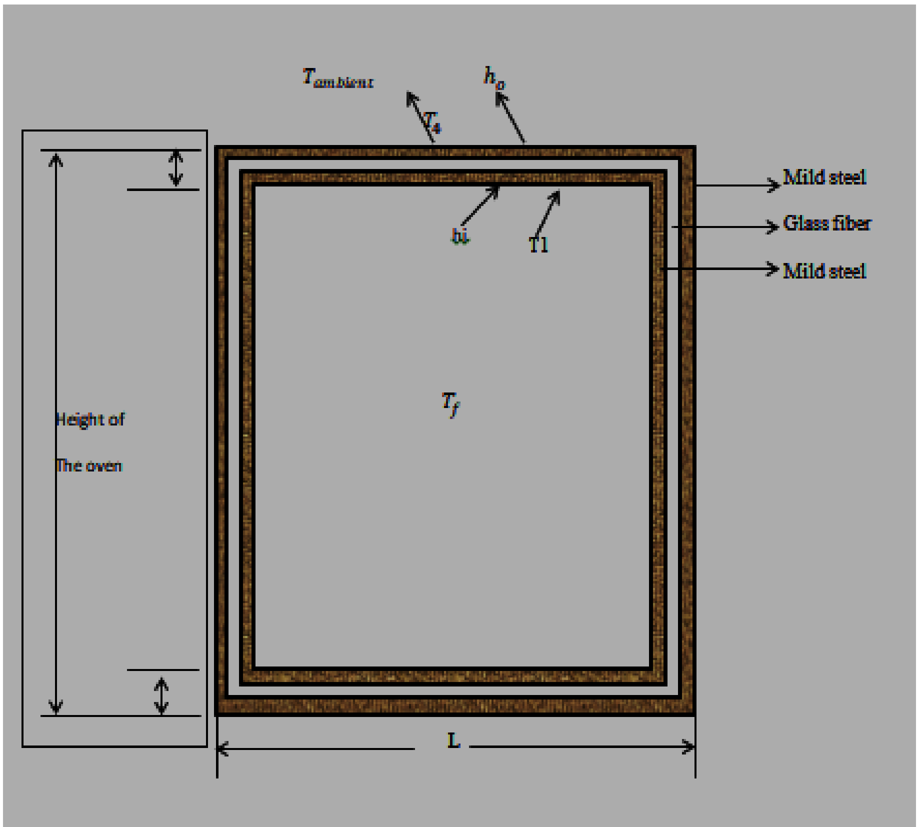

Figure 1: Geometry and Temperature for heat transfer through the composite oven walls

$$Q_1 = h_i A(T_f - T_1);\; Q_2 = \frac{K_1 A_1 (T_1 = T_2)}{X_1};\; Q_3 = \frac{K_2 A_2 (T_2 - T_3)}{X_2};\; Q_4 = \frac{K_3 A_3 (T_3 - T_4)}{X_3};\; Q_5 = h_o A(T_4 - T_\infty) \quad (10)$$

$$Q1 = Q2 = Q3 = Q4 = Q5 = Q \quad (11)$$

$$Q = h_i A\left(T_f - T_1\right) = \frac{K_1 A_1 (T_1 - T_2)}{X_1} = \frac{K_2 A_2 (T_2 - T_3)}{X_2} = \frac{K_3 A_3 (T_3 - T_4)}{X_3} = h_o A(T_4 - T_\infty) \quad (12)$$

$$Q1 + Q2 + Q3 + Q4 + Q5 = Q \quad (13)$$

$$Q = h_i A\left(T_f - T_1\right) + \frac{K_1 A_1 (T_1 - T_2)}{X_1} + \frac{K_2 A_2 (T_2 - T_3)}{X_2} + \frac{K_3 A_3 (T_3 - T_4)}{X_3} + h_o A(T_4 - T_\infty) \quad (14)$$

Assuming A = constant

$$Q = h_i A\left(T_f - T_1\right) + \frac{K_1 A_1 (T_1 - T_2)}{X_1} + \frac{K_2 A_2 (T_2 - T_3)}{X_2} + \frac{K_3 A_3 (T_3 - T_4)}{X_3} + h_o A(T_4 - T_\infty) \quad (15)$$

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$$(Tf - T\infty) = (Tf - T1) + (T1 - T2) + (T2 - T3) + (T3 - T4) + (T4 - T\infty) \quad (16)$$

$$T_f - T_\infty = \frac{Q}{h_i A} + \frac{QX_1}{k_1 A} + \frac{QX_2}{k_2 A} + \frac{QX_3}{k_3 A} + \frac{Q}{h_o A} \quad (17)$$

$$Q = \frac{T_f - T_\infty}{\frac{1}{A}[\frac{1}{h_i} + (\frac{X_1}{K_1}) + (\frac{X_2}{K_2}) + (\frac{X_3}{K_3}) + (\frac{1}{h_o})]} \quad (18)$$

$$Q = 92.7372W$$

For the four sides, the total heat loss is:

$$Q_T = 92.7372 \times 4 = 370.9488 \frac{J}{S}$$

Estimation Of Heat Transfer Coefficient

The convective heat transfer temperature is the mean temperature between T_4 and $T\infty$ i.e.

$$Mean\ Temp. = \frac{T_4 + T_\infty}{2} = \frac{183+30}{2} = 106.5°C \quad (19)$$

For free convection

$$Nu = 0.53(Pr.Gr.)^{0.2}\ for\ 10^4 < (Pr.Gr.) < 10^9 \quad (28)$$

$$Nu = 0.12(Pr.Gr.)^{0.33}\ for\ 10^9 < (Pr.Gr.) < 10^{12} \quad (29)$$

Where;

Nu = Nusselt number; Pr =Prandtel number; Gr = Grashoff number

Mathematically,

$$Pr = \frac{C_p \mu}{K} \quad (20)$$

WhereCp = specific heat capacity of air at 106.5°C; μ = kinematic viscosity at 106.5°C

K = thermal conductivity of air at 106.5°C; Pr = Prandtel number

$$Gr. = \frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} \quad (21)$$

WhereL = length of the oven; ρ = density of air; g = acceleration; β = coefficient of thermal expansion;

$$\Delta T = mean\ Temperature = 106.5°C$$

$$Nu = \frac{hcdc}{k} \quad (22)$$

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Were hc= heat transfer coefficient;

dc = characteristic dimension = $\frac{Volume_{oven}}{Area_{surface}}$= 1.8m. (23)

From thermophysical properties of matter table, the prandtel dimensionless property of air at 106℃ is 0.7099

While

Grashoff number = $\frac{L^3\rho^2 g\beta\Delta T}{\mu^2} = \frac{0.6^3 \times 0.9302^2 \times 9.81 \times 0.0034 \times 106.5}{(2.264X10^{-5})^2}$ =1.3188×10^9

Therefore,

$Nu = Prandtel \times Grashoff = 0.7099 \times 1.318810^9 = 9.3623 \times 10^8$ (24)

$$Nu = 0.53(Pr.Gr.)^{0.2}\ for\ 10^{\ 4} < (Pr.Gr.) < 10^9$$

$$Nu = 0.53(9.3623 \times 10^8)^{0.2} = 33.0029$$

Therefore,

$$h_c = \frac{Nu \times K}{d_c} = 0.5758 \quad (25)$$

Preparation of Dough

A quantity of flour was sieved into a mixing bowl; sugar, salt and yeast were all added and manually mixed together. The margarine was rubbed into the flour mixture and finally water was added just enough to form stiff dough. The dough was covered in the mixing bowl for about 45 minutes. It was then divided into four portions for easy working and each portion was worked and kneaded with occasional dusting with dry flour into a smooth and elastic pastry using a kneading pin. The kneaded dough was cut into small units of 200g each and then molded and placed into a greased bread pan dimensioned above. The dough was allowed to rise until tripled in size (dome shape forms above the age of the pan). The ripened dough was then loaded into the oven which had already been preheated and baked until a golden-brown crust colour was obtained. The loaves were de-panned and allowed to cool before sampling for sensory evaluation. For control purposes, the same dough was formulated and baked in a conventional gas-powered oven. The oven preheating time, baking time and efficiency was recorded. The flow chart and material balance for the bread production is shown in Figure 3.

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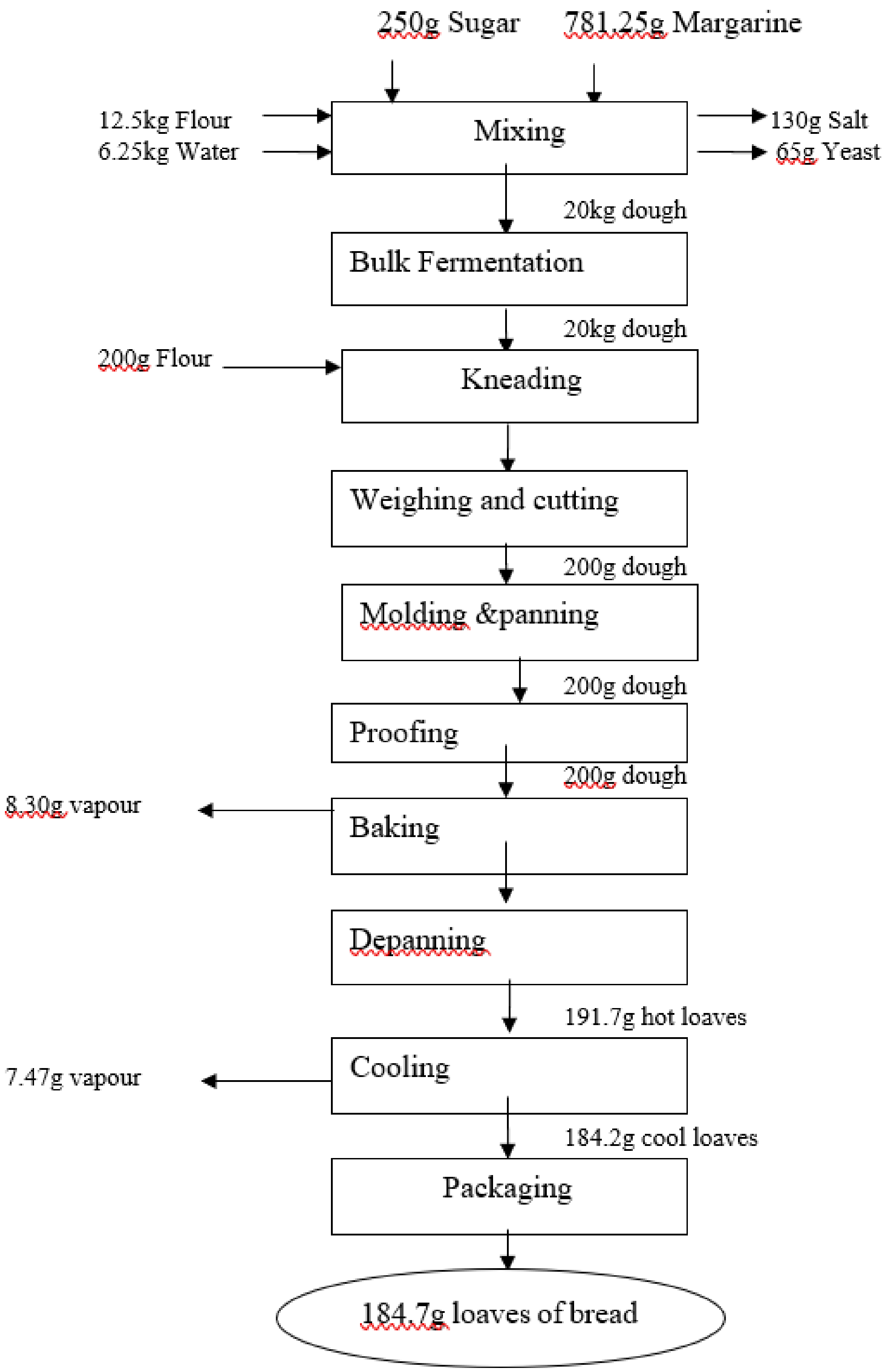

Figure 3: Flow Chart and Material Balance for Bread Production

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Sensory Evaluation of Bread Baked with the Oven

A 5-man sensory panellist was arranged from the staff of Food Technology Department, Akanu Ibiam Federal Polytechnic, Unwana for an organoleptic assessment of the oven and other baked products baked with the oven in terms of appearance, volume, crust colour, texture, flavour, taste and overall acceptance. A 9-point hedonic scale was used according to the method of Ihekoronye and Ngoddy (1985), whereby 9 = extremely liked, 8 = highly liked, 7 = moderately liked, 6 = slightly liked, 5 = neither liked nor disliked, 4 = slightly disliked, 3 = moderately disliked, 2 = highly disliked and 1 = extremely disliked. Products of similar recipe and configurations baked in a conventional gas-powered oven were used as the controls for the sensory evaluations.

Oven Performance Efficiency

$$Baking\ efficiency\ (\eta\%) = \frac{Work\ Output}{Work\ input} \times 100 = \frac{Heat\ load\ for\ baking\ of\ 100\ loafs}{Mass\ of\ dometic\ gas\ used \times Calorific\ Value} \times 100$$

RESULTS

The Table 2 below shows the material and cost implication of the design and fabrication of the gas-powered industrial oven. From the Table, the bill of engineering materials for the oven shows that the cost of fabricating the industrial oven makes it affordable for small, medium and cottage industries considering the capacity of the oven. Again, the materials used in the fabrication of the oven are all locally available materials and therefore ensures the availability of the oven spare parts to ease maintenance.

Table 2: Bill of Engineering Materials for the oven

S/N	Oven Component	Purpose	Qty	Unit cost (₦)	Amount (₦)
1	2mm gauge mild steel sheet	Outer and inner oven walls	41/2 sheets	16,000	72,000
2	10mm steel rod	For supporting baking racks	2 lengths	2,500	5,000
3	Fiber glass	Oven insulation	1 bag	20,000	20,000
4	Glass pane	See-through window	¼ sheets	2,000	2,000
5	Burner grills	Source of heat	2	10,000	20,000
6	Copper pipe	Gas inlet into the grills	1 coil	8,000	8,000
7	Angle bars	Framing of the oven	3lengths	5,000	15,000

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Table 3: Sensory evaluation table for bread baking

Sample	Appearance	Volume	Texture	Crust colour	Flavour	Taste	Gene. accept
CCBB	8±0.51	8±0.51	7±0.20	8±0.51	7±0.20	8±0.51	8±0.51
NFBB	8±0.51	8±0.51	7±0.21	8±0.51	8±0.51	8±0.51	8±0.51

Key: CCBB= Conventional Convective Baked Bread; NFBB= Newly Fabricated Baked Bread;

Gen. accept.= General acceptability

Table 3 shows the organoleptic properties of the bread baked with the conventional gas-powered convection oven (CBB) and the one baked with the newly fabricated gas-powered industrial oven (NFBB). From the result obtained, the sensory evaluation shows that there were no significant differences between the bread baked with the oven fabricated and the bread baked with another convective oven for all the attributes evaluated at $P \leq 0.05$. These properties include appearance, bread volume, texture, crust colour, flavor, taste and general acceptability.

Table 4: Oven Performance Evaluation

Parameters	Preheating time(min)	Baking time(min)	Baking efficiency
NFBO	25	30	70.79%
CTRO	25	52	42

KEYS: *NFBO = Newly Fabricated Oven; CTRO = Control Oven.*

Table 4 shows the performance evaluation of the oven against the control oven. The parameters evaluated include preheating time (min), oven baking time (min) and the baking efficiency (%). From the result of the performance analysis done on the oven, it was seen that when preheated for the same timeframe, the newly fabricated oven used 30 minutes to bake 100 loaves of bread weighing 200g each with 0.5kg of fuel (domestic cooking gas) with calorific value of 46.1MJ, while it took the control oven 52 minutes with more than 1kg of fuel to bake the same quantity of bread. This shows that the newly fabricated oven was more economical and therefore will generate more profit for the users while producing the same quantity and quality of baked food product. Also, from the result obtained from the baking efficiency of the ovens, the newly fabricated oven showed 70.79% efficiency while that of the control oven was a little above 40% (42%).

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CONCLUSION

In this work, a gas-powered convective oven built with locally available engineering material was successfully designed, developed and evaluated. This work proves that a more efficient directly heated oven can indeed be designed and constructed from locally available engineering materials for use in the baking of foods. The direct heating method and its simple design enabled the oven to be powered by domestic fuel (cooking gas). There was no significant difference in the organoleptic qualities between the foods baked with the oven and the ones baked with other conventional ovens ($p<0.05$). This gas-powered convective oven showed a better performance than the control oven when the baking time and baking efficiency of the machines were compared. This therefore shows that the locally fabricated oven is suitable and more economical for baking foods (snacks and pastries).

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