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Performance Analysis of a Developed Improved Thermally Insulated Fired Brick Baking Oven

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Abstract: *In Nigeria, there is a high demand for local baking ovens for various uses. Although most ovens do not follow modern scientific principles and procedures in the design and fabrication. In this paper, a two-chambered fired brick oven was designed and constructed for the production of bread using wood as the fuel source. Using design considerations, key design requirements such as heat required to bake bread, heat required in the oven, chamber design, chimney height and fuel requirement were determined. The doors of both the baking and combustion chambers were constructed from mild steel plates. Specifically, an optimized mixture of improved thermally insulated fired brick composed of 10%wt sawdust, 10%wt periwinkle shell ash and 1100 °C firing was used in the oven construction. The fabricated oven was preheated to 250°C at about 30 minutes and the bread was placed in the baking chamber and baked for 12 minutes consuming a total of 1.43 kg of wood as against the designed baking time of 30 minutes. This results to oven's baking time efficiency 2.5 times faster than the ideal design time. The heating rate of the oven was determined to be 7°C/min, while the cooling rate was approximately 0.5°C/min and this indicates that the heating rate is about 14 times faster than the cooling rate. Consequently, the oven produced in this study proved to be of lower thermal conductivity and relatively high compressive strength thereby reducing energy consumption challenges in the baking process.*

Keywords: *Baking Oven, Fired Bricks, Performance Analysis, Thermal Analysis, Design and Fabrication*

INTRODUCTION

Baking oven refers to a device or insulated edifice utilized in conducting baking and roasting activities. It comprises the application of dry heat conveyed by mixture of conduction convection and radiation form of heat transfer to process food. Baking oven is generally classified according to mode of heating such as direct or indirect heating; mode of operation like batch oven, semi-continuous or continuous oven; mode of heat transfer which could be natural or forced convection; as well as according to portability, as either fixed or portable oven (Andersen *et al.,* 2013; Davidson, 2016). In both cases, the baking process in the oven usually needs substantial high energy consumption as relatively high temperature is applied in order to remove moisture in bakery products and produce preferred texture.

A baking process accounts for 73 % of the energy consumption by sector in bakery industry out of nine sectors as indicated in Fig. 1.

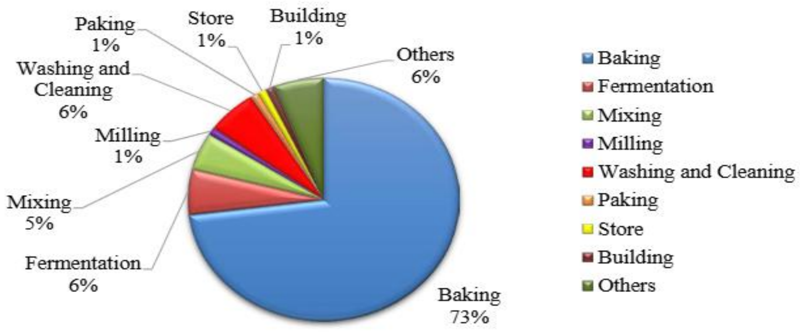

Fig. 1. Energy consumed by sector in bakery (Khoshkhoo and Omrani, 2017)

Historically, there are a range of issues that have prevented the adoption of energy efficient technologies in the baking industry. These include; product quality, hygiene fears, resistance to change, lack of capital investment and insufficient resources to enable technologies to be tried (Bramwell, 2013). Although, the contemporary current global political climate represents an opportunity for bakeries to make step changes to lower the energy demand of baking bread. A comprehensive examination comparing the energy consumption of indirect and semi-direct oven configurations in the baking process was conducted by Manhiça *et al.* (2012). The study revealed that up to 60 tons of green wood are consumed in East Africa daily during baking operations. Specific fuel consumption rates were meticulously determined, with the indirect oven requiring 0.55 kg of wood per kg of dough and the semi-direct oven consuming 0.90 kg for the same quantity of dough. These findings underscore the significant impact of oven configuration on energy usage, highlighting potential areas for optimization in bakery operations.

Kulla *et* al. (2014) investigated an economically viable oven design suitable for baking bread efficiently using minimal charcoal, offering a practical solution for both rural and urban settings. The study utilized a mild steel oven box measuring 80 x 50 x 50 cm, consuming only 0.2kg of charcoal for baking. The baking process lasted 25 minutes at a temperature of 140°C, with the oven achieving a temperature range between 32°C and 220°C. A locally fabricated bread oven fuelled by charcoal demonstrated functional efficiencies of 91.2% and 92.1% when baking dough of different masses (ranging from 0.5kg to 1.5kg). The baking times were recorded at 27.7 minutes and 35.9 minutes, with an average baking temperature of 153°C and 165.9°C, respectively (Alimasunya *et al.,* 2016). A study on the use of energy in oven for baking bread in the North central of Nigeria was conducted by Smah *et al.,* (2021). It was discovered that 47% of the sample's oven taken use wood/charcoal in Nasarawa State and 70% in Benue State. The study shows that a large number of bakeries uses wood/charcoal as fuel in their baking processes. The research reveals an estimated baking temperature of about 133.23 – 172.12^{o}C for oven in Nasarawa State and 160.38 - 200^{o}C in Benue State. The estimated baking time 27.5 ± 1.2min and 29.06 ± 1.99min for the respective states. It was also reported that in conventional oven, the temperature typically varies from 50 to 350°C. Among bakeries, approximately 50% operate within the temperature range of 151-250°C, 17% within 50-150°C, 3% within 251-350°C, and 30% lack knowledge about estimating their oven temperature. The survey revealed that the majority of bakeries reported a baking time within the range of 21-30 minutes, with more than half falling into this category. The second-highest category for baking time was in the range of 31-60 minutes. Begum *et al,* (2023) produced a biscuit and bread making electrical oven that is accessible and moveable. It was discerned that a bread crust temperature from 101.6 to 158.7°C was attained by enhancing an oven temperature from 160 to 200°C. Although, the temperature and weight of bread rise steadily with increasing baking time up to 18-20 min and subsequently began to decline until it reached balance after 30 min. The improved oven generated about 27.4% lesser moisture content in bread compared to conventional ovens thereby producing better quality bread.

Hence, the improved oven design serves as a more efficient alternative to traditional ones. A relative examination of diverse burner concepts (U, H and rectangular types) in a locally produced bread-baking oven was performed by Kofi *et al.* (2024). The oven made from galvanized steel plate consist of a housing compartment of 450 x 380 x 350 mm, thermocouple ports, a gas nozzle outlet, and a heating gas burner. The results disclosed that the concept burners can be utilised to bake bread with enhanced outcomes in terms of texture, taste and colour within efficient baking time. The study revealed that reduction in baking time and enhanced baking efficiency was attained using rectangular. This could be attributed to its ability to produce a high amount of heat within the oven chamber. A unique wood-fired commercial oven was designed and constructed by Akinwonmi (2024) solely for bread baking. The oven comprised exterior combustion section with heating elements connected to 3 oven chambers each having 12 heating elements. The elements are positioned beneath a mild steel sheet metal where the prepared dough and its content is placed. A silica brick and fibre glass walls were used to prevent heat loss through conduction, convection and radiation from the oven and combustion chamber compartments respectively. Findings from the study revealed that the oven attained a peak temperature of 700°C, although, only a temperature range of 150°C and 180°C was adequate for baking bread. The duration for the bread baking was 25 minutes and the amount of heat energy produced per time using 10 kg of wood was about 15.1 MJ. Geda *et al.* (2025) designed and constructed a small-scale, portable, wood-powered bread-baking oven. The oven was evaluated based on its baking capacity, efficiency, and the weight loss of the bread produced as 160 loaves, 86.9% and 12.6% respectively. The oven's performance in terms of baking time for 100g – 2kg loaves of bread was between 15 - 25 minutes using a single feeding of 5 kg of biomass fuel. Consequently, the authors suggested for use of the oven in small-scale enterprises and domestic set-up.

Generally, in Nigeria, there is a high need for local baking ovens, predominantly among bakers, food industries and caterers for various baking uses such as bread, cake, meat pie and fish. Aside enhanced energy efficiency, the locally produced baking ovens are proved to be reliable and durable; cost effective; ease of use and operation as well as flexibility in fuel type (Salisu, 2024). However, most small-scale baking ovens are built by the local workers and usually no scientific principles are followed to design and build of it. Hence, it is imperative for modern scientific principles and procedures to be followed to design and fabricate the baking ovens using low-cost materials. In the present study, an improved thermally insulated fired brick baking oven was designed and fabricated locally for the production of bread. It explores strategies to enhance heat retention in baking ovens by modifying the thermal conductivity and compressive strength of clay (Kaolin) using sawdust and periwinkle shell ash additives. The basic objective function is lower thermal conductivity and relatively high compressive strength which reduces energy consumption challenges in the baking process. A baking oven is an enclosed thermal insulated chamber that utilizes heat energy for efficient baking and drying process. The transmission of heat energy from one region to another as a result of the temperature gradient is referred to heat transfer (Jiji and Danesh-Yazdi, 2024). The heat energy moves from a region of higher concentration to a region of lower concentration as supported by the second law of thermodynamics. In most cases, heat transfer takes place in three modes which is applicable to baking oven in this study for carrying out the baking operation. Heat is transferred to the dough via convection and radiation and through the centre of the dough by conduction and the modes of heat transfer relative importance is determined if the oven is a forced convection or natural convection type. The three modes of heat transfer are convection, conduction and radiation (Khatir *et al.*, 2015). Convection is the transfer of heat within a fluid by mixing of one portion of the fluid with another (Jiji and Danesh-Yazdi, 2024). The convection heat transfer constitutes the macroscopic movement of the fluid particles causing the heat exchange of which its effectiveness is greatly measured by the mixing strength of the fluid particles in transport Kulla *et al.* (2014). This mode of heat transfer is met with in situation where energy is transferred as heat to a flowing fluid at any surface over which flowing occurs. It is basically conduction in a very thin layer at the surface and then mixing cause by the flow. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is purely by conduction. However, the shape of the surface will influence the flow and hence the heat transfer. Heat transfer by convection is further classify in to forced and natural convection. Forced convection is simply when the work is done by an external medium like fan, pump to aid the mixing of the fluid particles.

Natural or free convection occurs when the fluid circulates by virtue of the natural difference in densities of hot and cold fluids; the denser portion of the fluid moves downward because of its greater force of gravity as compared with the force of the less dense. Despite the complexity in convection, the rate of heat transfer according to Rajput (2007) is calculated using the Newton's law of cooling given in Equation 1 as,

$$Q_{conv} = hA_s(T_s - T_\infty) \tag{1}$$

where Q_{conv} is the rate of convective heat transfer in Watt(W), h is the convective heat transfer coefficient in W/m², A_s is the surface through which the convective heat transfer takes place in m², T_s is the surface temperature and T_∞ is the temperature of the fluid far from the surface measured in °C. The transfer of heat energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, and gases. In liquids and gases, conduction is due to the collision and diffusion of the molecules during their random motions. In solids, it is due to the combination of vibration of the molecules in a lattice and the energy transport by free electrons. The rate of heat conduction through a medium depends on the geometry of the medium, its thickness, and the material of the medium as well as the temperature difference across the medium (Jiji and Danesh-Yazdi, 2024). Heat transfer rate via conduction is explained by Fourier's law of heat conduction which states that "the rate of heat transfer through a plane layer is directly proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer (Rajput, 2007; Kulla et al., 2014).

$$Q_{cond} = -KA\frac{dT}{dx} \tag{2}$$

where Q_{cond} is the conductive heat transfer rate in W, k is the thermal conductivity and it is material dependent in W/mK, A is the area through which the heat transfer takes place in m², and dT/dx is the temperature gradient along a thickness. The –ve sign takes care of the decreasing temperature along with the direction of increasing thickness or direction of heat flow. For composite materials; the total heat flow is given in Equation 3 and Equation 4 as:

$$Q = \frac{dT}{\sum R} = \frac{T_1 - T_2}{\sum R} \tag{3}$$

where T_2 is the temperature on the outer surface, T_1 is the temperature on the inner surface and $\sum R$ is the heat resistance through the wall.

$$\sum R = \frac{L_a}{h_i A} + \frac{L_a}{h_o A} + \frac{L_a}{K_a A} + \frac{L_b}{k_b A} + \frac{L_c}{k_c A} \tag{4}$$

where R denotes resistance to heat flow, h_i and h_o = inner and outer convective heat transfer coefficient, A is cross sectional area, L_a, L_b and L_c represent thickness of materials a, b, c, whereas K_a, K_b and K_c is the conductive heat transfer co-efficient for materials a, b and c. Radiation is the energy emitted by matter in the form of electromagnetic waves as a result of changes in the electronic configurations of the atom or molecules. Unlike conduction or convection, the transfer of energy requires no material medium for propagation and the energy is transferred through a vacuum at the speed of light and suffer no attenuation (Jiji and Danesh-Yazdi, 2024). A typical example is the transmission of solar energy by sun to the surface of earth. The maximum rate of radiation that could be emitted from a body at an absolute temperature is given by Stefan-Boltzmann law in as Equation 5 and Equation 6 as:

$$Q_{rad\ max} = \sigma A_s T_s^4 \tag{5}$$

$$Q_{rad} = F\sigma A_s(T_1^4 - T_2^4) \tag{6}$$

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where Q_{rad} is the radiative heat transfer rate in W, **σ** is Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4), A_s is the surface area of heat transfer in m^2, T_s is the absolute temperature in K, F is a factor depending on the geometry and surface properties.

MATERIALS AND METHODS

2.1 Oven Description

The present study encompasses the construction of a *'mini-indirect baking oven'* featuring two distinct chambers: the baking chamber and the combustion chamber. The design prioritized simplicity to facilitate fabrication. The baking chamber, configured in a cuboidal shape, was tailored to accommodate a 15cm by 30cm tray, allowing for the simultaneous baking of items such as two small loaves of bread to enhance efficiency. The combustion chamber was engineered to transmit heat through conduction to the baking chamber via an aluminium sheet. It serves as the space for the fuel source (firewood), and openings were incorporated to ensure ample oxygen supply for complete fuel combustion. A grate is included for ash collection resulting from burnt fuel. The doors of both the baking and combustion chambers were constructed from steel plates. A thermometer is integrated into the baking chamber to monitor internal temperature, and an opening facilitates easy observation of oven activities. The oven design incorporates a chimney to expel fumes from the wood fuel, reducing moisture content within the baking chamber. The oven primarily consists of refractory materials produced from the material composition mix designed for optimal thermal insulation which in turn aided energy conservation. An optimized mixture of improved thermally insulated fired brick composed of 10%wt sawdust, 10%wt periwinkle shell ash and 1100 ^oC firing was used in the oven construction. Fig. 2 shows an engineering design and 3D model of the bread oven for the present study.

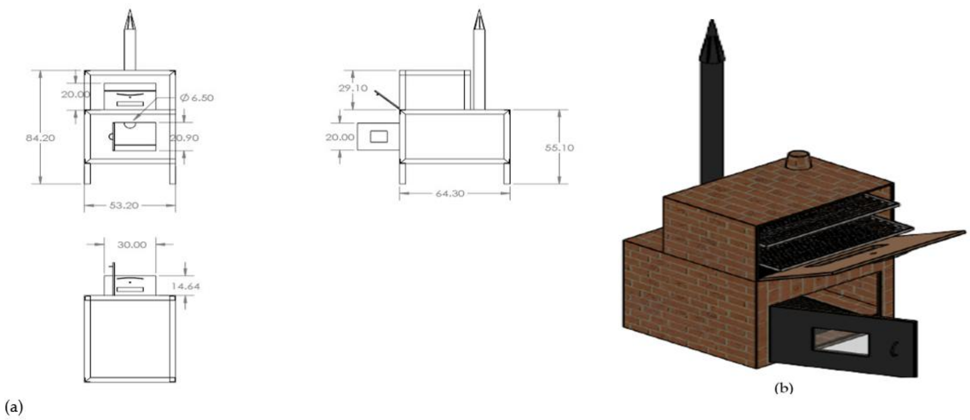

Fig. 2. Engineering design (a) and 3D model (b) of the locally fabricated bread oven

2.2 Design Consideration of the Baking Oven

The following design consideration are strictly adhered to in our design of the baking oven in this research work:

i. The oven was designed for simplicity and ease of use.
ii. The oven was designed for single tray slot.
iii. The oven utilizes one batch production process.
iv. The oven was designed to use a constant gradual heating process.
v. The oven was designed for separate baking and combustion chamber for minimal contamination.
vi. The fuel type consideration is the wood of LHV 19MJ.
vii. The accessibility and availability of the construction materials.
viii. The chimney design was considered for adequate mass transfer process.
ix. Oven feeding was an all-in once and all out once mechanisms.

x. Ease of removal of ash.
xi. Adequate design for sufficient air flow to aid combustion.

2.3 Design Conditions and Assumptions

The design requirements in this study are expressed in Table-1.

Table-1. Design conditions and assumptions

S/N	Items	Conditions & Assumptions	Reference
a.	Ambient temperature, T_a	30 °C	Kulla et al. (2014)
b.	Baking Temperature, T_b	213 °C	
c.	Specific heat capacity of bread dough, C_d	2800 J/kgK	(Alimasunya *et al.* 2016)
d.	Initial Temperature of oven air, T_i	30 °C	-
e.	Initial Temperature of oven bricks, T_{br}	30 °C	-
f.	Air Density, ρ_{air}	1.225 kg/m³	Property Tables/Chart
g.	Average air Velocity, V_{air}	3.0 m/s	Weather Atlas (2023)
h.	Adiabatic Flame Temperature of wood, T_w	1110 °C	Simulation
i.	Density of wood	790 kg/m³	(Asibor *et al.*, 2019)
k.	Heat transfer coefficient (h)	13 $Wm^{-2} K^{-1}$	(Carson *et al.*, 2006)

2.4 Design of Heat Required to Bake Bread

The heat required to satisfactorily bake the product in the oven is calculated using Equation 7 as:

$$Q_{dough} = mC_p\Delta T \quad (7)$$

where Q_{dough} is quantity of heat required (J), m is mass of bread dough at maximum loading, C_p is the specific heat capacity of dough and ΔT is difference in temperature between the tropical ambient and that of baking.

2.5 Heat Required in the Oven

The heat required in the oven is given in Equation 8 as:

$$Q_{total} = Q_{dough} + Q_{air} + Q_{Altray} + Q_{loss} + Q_{rad} \quad (8)$$

where Q_{total} is the total heat required by the oven, $Qdough$ is the heat required to cook the dough, Q_{air} is the heat required to heat up the film if air in the oven, Q_{Altray} is the heat required by the baking tray, Q_{loss} is lost through the wall by air film to the outside environment, Q_{rad} is the heat radiated by the Aluminum sheet.

2.6 Combustion Chamber Design

The design of the combustion chamber is tailored to supply the necessary heat to the baking chamber, taking into account the heat release rate of wood, which is 3.5 MW/m², and the Lower Heating Value (LHV) of the wood, measured at 19MJ/kg. Following the analysis of 10 wood samples (Ohian, Otu, Apa, Okwen, Albizia, Bombax, Ukpe, Acacia, Obeche and Ekhimi), Apa otherwise known as Afzelia Africana emerged as the most suitable choice for energy generation due to its superior energy content (Asibor *et al.*, 2019). A proximate analysis of the Apa wood revealed a composition of 0.46% fixed carbon, 88.23% volatile matter, 10% moisture content, and 1.31% ash. The Apa's ultimate analysis revealed its elemental composition of 45.7% carbon, 5.86% hydrogen, 48.32% oxygen, 0.1% nitrogen, and 0.01% sulphur. The wood density is reported as 790 kg/m³, with a calorific value of 19,066 MJ/kg and an energy content of 15,065.3 MJ (Asibor *et al.*, 2019). According to Novaes *et al.* (2010), wood fundamentally comprised of two primary components: cellulose, constituting approximately 40-45% of the wood's dry weight and serves as the principal chemical constituent of the fibre wall; and lignin, accounting for around 21-30%. The air-fuel ratio (AFR) for the thorough combustion of wood was determined through the use of the ultimate analysis formula for solid fuels given in Equation 9 as:

$$AFR = 11.5C + 34.5\left(H - \frac{O}{8}\right) + 4.3S \quad (9)$$

Equation 10 was used in the calculation of the volume of air needed for the complete combustion of the wood.

$$v = \frac{m}{\rho} \quad (10)$$

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The opening air inlet area required to accommodate the calculated volume of air per second in the combustion was calculated using the Equation 11 and volumetric air flow rate (Q) from Equation 12 as:

$$Q = \frac{v}{t} \quad (11)$$

$$Q = A.v \quad (12)$$

Where v, is the total volume of air for complete combustion (m^3), m is the mass of air (kg), ρ is the density of air (kg/m^3), Q is the volumetric flow rate of the air (m^3/s), A is the surface area of the opening to accommodate the air volume in sec (m^2), v is the wind velocity (m/s) and t is the baking time (s). The mass flow rate, (m_f) was calculated knowing the heat release rate and the lower heating value of the wood using Equation 13.

$$Q_{fuel} = m_f * LHV \quad (13)$$

With an average density of Afzelia Africana (Apa) given as $790kg/m^3$ given by Asibor, *et al.* (2019), the wood volume of 1kg, V_w can be calculated from Equation 14.

$$V_w = \frac{Mass\ of\ wood}{Density\ of\ wood} \quad (14)$$

Using the Heskestad equation, the flame height of the burning fuels is considered in order to account for the combustion chamber space for the fuel-efficient combustion, the flame height of the fuel was calculated using the Equation 15 as given by Bubbico, *et al.* (2016).

$$H_f = 0.235Q^{2/5} - 1.02D \quad (15)$$

Where H_f is the flame height (m), Q is the heat release rate (kW) of the fuel and D is the diameter of the burner (m). Since the fuel configuration is square, it is necessary to convert the fuel surface area to an effective diameter for the direct application of Heskestad's flame height equation. Consequently, a wood geometry surface area was transformed in this study to determine the effective diameter. The overall height of the combustion chamber was designed with careful consideration of the flame height during wood combustion.

2.7 Design of the Chimney Height

The chimney was designed to expel moisture from the baking material and creosote flames resulting from the combustion of fuel wood into the atmosphere. The design of the chimney height was determined by the Sulphur dioxide content of the wood fuel utilized in the process. Equation 16 was employed in the calculation of the chimney height whereas 17 was for determining the quantity of Sulphur dioxide respectively:

$$H_{ch} = 14Q^{0.3} \quad (16)$$

$$Q = \frac{Quantity\ of\ fuel\ \left(\frac{kg}{hr}\right) * Suplhur\ dioxide\ content\ (\%) * 2}{100} \quad (17)$$

Where H_{ch} is the height of the chimney (m), Q is the quantity of Sulphur dioxide in the fuel wood (kg/hr).

2.8 Oven Construction and Baking Testing

A two-chambered indirect-fired brick oven presented in Fig. 3 was constructed for practical applications, consisting of a combustion chamber (20 x 30 x 30) cm and a baking chamber (20 x 20 x 30) cm. An optimized insulation material from this research was employed in the fabrication, ensuring efficient heat retention. In this setup, wood serves as the fuel source in the combustion chamber, and the heat is transferred to the baking chamber, which is separated from the combustion chamber by a thin sheet of aluminium metal. The prototype oven was specifically designed for real-life applications, with a focus on baking, and bread was chosen as the experimental food product for testing.

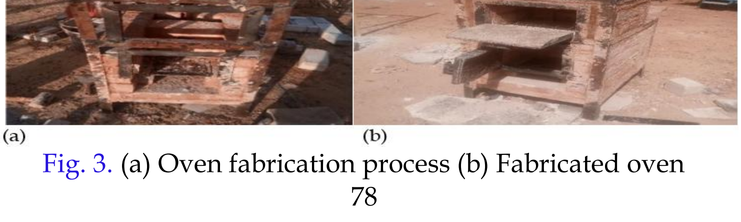
(a) (b)

Fig. 3. (a) Oven fabrication process (b) Fabricated oven

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Considering the dimensions of the oven's baking chamber (30 x 20) cm, a dough weighing 1 kg was meticulously prepared and placed in two rectangular pans (18 x 8) cm, each with a height of 7 cm. The dough was covered with cellophane and allowed to rise for approximately 1 hour, reaching about twice its original size. Subsequently, the oven was preheated to 250 degrees Celsius, with a baking temperature ranging from 200 to 213 degrees Celsius. The preheating process took around 30 minutes to achieve the desired temperature. Following the preparation, the bread was placed in the baking chamber and baked for 12 minutes, resulting in two loaves from the 1 kg dough. The heat source was then removed. Additional batches of 2 kg of bread (1 kg per batch) were baked successively, bringing the total bread production to 3 kg. Even after all the baking, the oven's temperature remained well above 100 degrees Celsius.

RESULTS AND DISCUSSION

3.1 Oven Construction and Baking Testing

Table 2 presents the results of the design calculation employed in the fabricated oven.

Table-2. Design data and calculation of the Oven

Initial data	Calculation and Sketches	Results
m_d = 0.5kg, C_p dough = 2.8 kJ/kg-K $\Delta T = 213^oC$, time = 30 min	3.1.1 Heat required to cook  From Equation 7, $Q_{dough} = mC_p\Delta T$ $Q_{dough} = \frac{0.5\,kg}{30\,mins}\left(\frac{1\,min}{60s}\right) * 2.8\,\frac{kJ}{kg/K} * 213$ = 0.16566kW = 165W	Q_{dough}= 165W
	3.1.2 Oven heat energy From Equation 8, $Q_{total} = Q_{dough} + Q_{air} + Q_{Altray} + Q_{loss} + Q_{rad}$ $Q_{total} = Q_{air} + Q_{aluminium} + Q_{steel} + Q_{dough} + Q_{losses} + \quad Q_{radiation}$ $Q_{total} = Q_{oven} + Q_{losses}$ $Q_{oven} = \frac{T_{cooking} - T_{initial}}{Summation\ of\ resistances} + Q_{dough} + Q_{radiation}$ $Heat\ resistance = \frac{Thickness}{Thermal\ conductivity * Heat\ transfer\ area}$ A_{tray}= 0.15 m x 0.3 m x 2 Aal_{sheet}= 0.2 m x 0.3 m $A_{brick} = A_{bc} + A_{cc}$ $A_{bc} = A_{fw} + A_{bw} + A_{lw} + A_{rw} + A_{tw}$ A_{bc} = (0.3 * 0.2) + (0.3 *0.2) + (0.2 * 0.2) + (0.2 * 0.2) + (0.3 * 0.2) $A_{cc} = A_{fw} + A_{bw} + A_{lw} + A_{rw} + A_{bw}$ A_{cc} = (0.3x0.3) + (0.3 x 0.3) + (0.2x0.3) + (0.2 x 0.3) + (0.3 x 0.2) $A_{brick\ wall}$= 0.36 + 0.26 = 0.62m² Heat transfer Area for inside film of air = Heat transfer area of brick wall Heat transfer area for inside film of air = 0.62 m²	$A_{bc} = 0.26m^2$ $A_{cc} = 0.36m^2$ $A_{brick\ wall}$ = 0.62 m²
	3.1.3 Heat transfer area for outside film of air for heat lost to the environment $A_{brick\ wall\ outside} = A_{of} + A_{ob} + 2(A_{o-LR}) + A_{o-bt} + A_t$ $A_{brick\ wall\ outside}$ = (0.3500) + (0.4733) + 2 (0.3645) + (0.3304) + (0.2041) = 2.0868 m	$A_{brick\ wall\ outside}$ = 2.0868 m^2
h_{air} = 13 W/m²K	3.1.4 Baking chamber heat Using Equation 3, $Q = \frac{dT}{\Sigma R} = \frac{T_1 - T_2}{\Sigma R}$ $Q_{bc} = \frac{(213-21)}{2\,x\,\frac{0.002m}{237\frac{W}{m-K}\,x\,0.15\,x\,0.3m^2} + \frac{0.002m}{237\frac{W}{m-K}\,x\,0.2\,x\,0.3m^2} + \frac{1}{13\frac{W}{m-K}\,x\,0.62}}$ Q_{bc} = 1741.56W	Q_{bc} = 1741.56W

Jimoh *et al.* (2026). *Performance Analysis of a Developed Improved Thermally Insulated Fired Brick Baking Oven*. *Nigeria Journal of Engineering Science Research (NIJESR), 9(1), 72-83.* https://doi.org/10.5281/zenodo.20191346

	Heat losses; Q_{loss} = Heat transferred to inside film of air, to the walls, to the outside film of air then to the environment. $Q_{loss} = \frac{(213-21)}{2\,x\,\frac{0.112m}{0.4\frac{W}{m-K}\,x\,0.62m^2} + \frac{1}{13\frac{W}{m-K}\,x\,0.62\,m^2} + \frac{1}{13\frac{W}{m-K}\,x\,2.0868\,m^2}}$ Q_{loss}= 298.75W $Q_{total} = Q_{fuel} = Q_{bc} + Q_{loss}$ = 1741.56 + 298.75 = 2040.31W Q_{total} = 2040.31W	Q_{loss}= 298.75W Q_{total} = = 2040.31W
	3.1.5 Thermal efficiency $\eta_{th} = \frac{Q_{bc}}{Q_{total}}\,x\,100$ $\eta_{th} = \frac{1741.56}{2040.31}\,x\,100$ = 85. 3576	η_{th} = 85.36 %
LHV = 19 MJ/kg	3.1.6 Wood mass flow rate From Equation 13, $Q_{fuel} = m_f * LHV$ $mass\ flow\ rate\ of\ wood, m_f = \frac{2040\,W\left(\frac{1kW}{1000W}\right)}{\frac{19{,}000\,kJ}{kg}}$ m_f = 1.0737 x 10^{-4} kg/s = 0.3865 kg/hr or 0.1933 kg/30 mins	0.1933 kg/30 mins
0.1% N, 45.70% C 5.86% H 48.32% O	3.1.7 Air required for the combustion Using approximate formula for air-fuel ratio for solid (wood) fuels as indicated in Equation 9. $AFR = 11.5C + 34.5\left(H - \frac{O}{8}\right) + 4.3S$ $= 11.5 * 0.4570 + 34.5\left(0.0586 - \frac{0.4832}{8}\right) + 4.3 * 0.001 = 5.1938$ Mass of air needed = $AFR * m_f = 5.1938\,\frac{kg\ air}{kg\ wood} * (0.3865\,kg/hr)$ = 2.0076 kg/hr= 5.5765 x 10^{-4} kg/s	Air-fuel ratio = $5.1938\,\frac{kg\ air}{kg\ wood}$ $Mass_{air}$ = 2.0076 kg/hr
V_{air} = 0.1 m/s ρ_{air} = 1.2 kg/m^3	3.1.8 Area needed for air intake during combustion For wood fuel: Mass of air needed = $5.5765\,x\,10^{-4}\,kg/s$ Mass of air needed = density air * area * velocity of outside air Area = $\frac{5.5765\,x\,10^{-4}}{1.2\frac{kg}{m^3}\,x\,0.1\,m/s}$ = 0.004647 m^2	Area = 0.0046 m^2
0.05 % SO_2	3.1.9 Chimney height Using Equations 16 and 17, $H_{ch} = 14Q^{0.3}$ $Q = \frac{Quantity\ of\ fuel\left(\frac{kg}{hr}\right) * Suplhur\ dioxide\ content\ (\%) * 2}{100}$ $H_{ch} = 14 * (7.4937\,x\,10^{-5})^{0.3}$	Q = $7.5\,x\,10^{-5}\,kg/hr$ H_{ch} = 0.8100 m

Fig. 4 shows the bread baked from the locally fabricated oven. Throughout the entire baking test, a total of 1.43 kg of wood was used as fuel. For the baking operation, 2 kg of wood was loaded into the combustion chamber using the "fire and forget" method. The remaining wood chars, still capable of serving as fuel, were carefully weighed to determine the total fuel consumption for the entire baking process as described with Fig. 5.

Fig. 4. Loaves of bread produced from locally constructed baking oven.

a b c

Fig. 5. (a) Total mass of wood used (b) Burning of the wood after loading in the Combustion Chamber (c) Mass of the fuel remaining after baking

To examine the impact of the fired brick samples on the overall thermal performance of the baking oven, an energy analysis was conducted. With the expectation that the optimized thermal bricks enhance thermal conservation and increase heat transfer through convection, while minimizing heat loss through conduction in the oven walls. The thermal efficiency of the oven was assessed through the specific consumption of energy. The specific consumption (SC), as defined by Manhiça *et al.* (2012), represents the amount of energy input required to perform a given task and is expressed mathematically in Equation 18 and Equation 19, these equations were used to calculate the oven cooking efficiency.

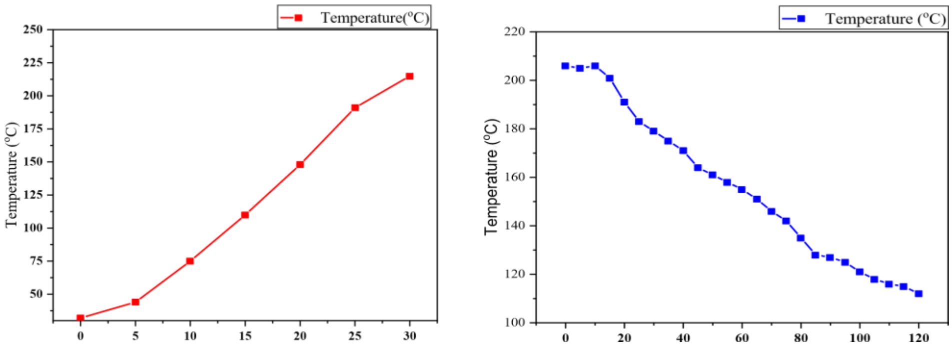
$$SC = \frac{mass\ of\ fuel\ wood\ consumed}{mass\ of\ bread\ baked} \quad (18)$$

$$\eta_{cooking} = \frac{1}{SC}\frac{C_{pt}\ .\ \Delta T}{HHV} \quad (19)$$

Where Cpt is the specific heat capacity of the food products and HHV is the higher heating value of the fuel. The baking efficiency using the ideal baking time and the actual baking time as reported by Ilesanmi and Akinnuli (2019) is calculated using Equation 20 as:

$$\eta_{baking} = \frac{design\ baking\ time}{actual\ baking\ time} \quad (20)$$

The energetic analysis of the oven, as calculated using Equation 18, (1.43 kg/3 kg) yielded a specific wood consumption of 0.48 kg of wood per kg of flour baked. Utilizing Equation 19, which establishes the relationship between specific consumption and cooking efficiency, the calculated cooking efficiency of the oven is 55%. Furthermore, the efficiency of the oven in Equation 20 is evaluated using the time required to bake a batch of dough to the desired quality in terms of taste, color, texture, and moisture content. The performance test indicated that it took 12 minutes to achieve the desired quality, while the design baking time for the dough was set at 30 minutes. Consequently, the baking time efficiency (η) is efficiency is 2.5 times faster than the ideal design time. In Fig. 6, the experimental results for the heating and cooling rates of the oven constructed with the insulation fired bricks material are presented. Notably, the heating rate of the oven was determined to be 7°C/min, while the cooling rate was approximately 0.5°C/min. This indicates that the heating rate is about 14 times faster than the cooling rate. This characteristic is advantageous for the insulation material when applied in a real-world scenario such as an oven. In contrast to the conventional definitions of heating and cooling rates, where heating rate represents how fast a material absorbs heat during a temperature increase and cooling rate reflects how quickly a material loses heat during a temperature decrease, the insulation material used in this oven demonstrates low thermal conductivity. As a result, when the heat source is active, the baking chamber heats up rapidly due to the constant supply of heat from the combustion chamber. Conversely, when the heat source is removed, the device loses heat slowly, contributing to a prolonged cooling process. In the experiment, it takes 30 minutes to heat up the baking chamber to a temperature of about 200°C and more than 500 minutes for the chamber to naturally cool down to its starting temperature, equivalent to the ambient temperature of 33°C. A significant factor influencing the heating and cooling rates of the material is thermal conductivity, which is substantially reduced (75%) in the material used for oven fabrication.



(a) Time (min) (b) Time (min)

Fig. 6. (a) Heating curve (b) Cooling curve of the oven.

CONTRIBUTION TO KNOWLEDGE

A two-chambered fired brick oven was designed using scientific approach and constructed locally for the production of bread using wood as the fuel source. Consequently, the produced oven proved to be of lower thermal conductivity and relatively high compressive strength thereby reducing energy consumption challenges in the baking process. The study has thus contributed to the field of mechanical and chemical engineering as well as food processing industry.

CONCLUSION

In the present study, an improved thermally insulated fired brick mini-indirect baking oven was designed and fabricated locally for the production of bread. The oven featured two distinct chambers namely the baking chamber and the combustion chamber. A dough weighing 1 kg was meticulously prepared and placed in two rectangular pans. Subsequently, the oven was preheated to 250°C, with a baking temperature ranging from 200 to 213°C. The energetic analysis of the oven, yielded a specific wood consumption of 0.48 kg of wood per kg of flour baked with a calculated cooking efficiency of the oven being 55%. The performance test indicated that it took 12 minutes to achieve the desired quality, while the design baking time for the dough was set at 30 minutes. Consequently, a baking efficiency time of 2.5 times faster than the ideal design time was attained. It was observed that the heating rate of the oven was 7°C/min, while the cooling rate was approximately 0.5°C/min. This indicates that the heating rate is about 14 times faster than the cooling rate. Equally, it took 30 minutes to heat up the baking chamber to a temperature of about 200°C and more than 500 minutes for the chamber to naturally cool down to its starting temperature, equivalent to the ambient temperature of 33°C. Therefore, the oven produced in this study proved to be of lower thermal conductivity and relatively high compressive strength which reduces energy consumption challenges in the baking process.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

REFERENCES

Akinwonmi, A.S. (2024). Design and Fabrication of a Novel Commercial Baking Oven. *American Journal of Mechanical and Materials Engineering*, 8(3), 39-46

Alimasunya, E., Yahaya, O., Muhammed, N. (2016). Development and Evaluation of Charcoal-Powered Bread Baking Oven. *Studia Engineering*, 23 (1), 23-30

Andresen, M.S., Risum, J. and Adler-Nissen, J. (2013). Design and Construction of a Batch Oven for Investigation of Industrial Continuous Baking Processes. *Journal of Food Process Engineering,* 36 (4), 500-509

Asibor, J.O., Akhator, E.P. and Obanor, A.I. (2019). Energy Potential Study of Some Tropical Wood Species from Nigeria. *Current Journal of Applied Science and Technology*, 37 (4), 1-10

Begum, A.A., Umme Habiba, U., Aziz, M.G., Mazumder, A.R. (2023). Design of an Improved Traditional Baking Oven and evaluation of Baking Performance. *Journal of Bangladesh Agricultural University,* 21(2), 203–213

Bramwell, P.J. (2013). *Energy Utilisation in Commercial Bread Baking*. PhD Thesis, University of Leeds

Bubbico, R., Dusserre, G., Mazzarotta, B. (2016). Calculation of the Flame Size from Burning Liquid Pools. *Chemical Engineering Transactions*, 53, 67-72

Carson, J., Willix, J., North, M. F. (2006). Measurements of Heat Transfer Coefficients within Convection Ovens. *Journal of Food Engineering*, 72 (3), 293-301

Curkeet, R. (2011). Wood Combustion Basics: in EPA Workshop March 2, 2011Davidson, I. (2016). Oven Designs: in book: *Biscuit Baking Technology: Processing and Engineering Manual*. 2nd Edition. Academic Press

Geda, U.K., Washi, A.H., Gemechis Mideksa Adugna, G.M. (2025). Renewable and Sustainable Energy Engineering Technologies, Adaptation and Evaluation of Small-Scale Portable Wood Powered Bread Baking Oven. *International Journal of Food Science and Biotechnology*, 10 (4), 98-111

Ilesanmi, O.E., Akinnuli, B.O. (2019). Design, Fabrication and Performance Evaluation of a Domestic Gas Oven. *Journal of Engineering Research and Reports*, 5 (1), 1-10

Jiji, L. M., Danesh-Yazdi, A. H (2024). *Heat Conduction.* 4th Edition: Springer Nature

Khatir, Z., Taherkhani, A.R., Paton, J., Thompson, H., Kapur, N. and Toropov, V. (2015). Energy Thermal Management in Commercial Bread-Baking Using a Multi-Objective Optimisation Framework. *Applied Thermal Engineering*, 80, 141-149.

Khoshkhoo, R. H., Omrani, M. M. (2017). Energy Audits and Recovery in the Production of Industrial Bread and Pastry. *3rd Conference on Advances in Mechanical Engineering (ICAME 2017),* Istanbul, Turkey, 19-21 December 2017, pp: 156-171

Kofi, S., Kwabena, O., Addai, B. Anto, M. (2024). Comparative Analysis of Different Burner Concepts in a Locally Manufactured Bread-Baking Oven. *International Journal of Energy Power Engineering*, 13(3), 42–51

Kulla, D. M., Ebekpa, I. M., Sumaila, M. (2014). Design and Construction of a Small-Scale Charcoal Baking Oven. *International Journal of Recent Development in Engineering and Technology*, 2 (6), 89-94

Manhiça, F.A., Lucas, C., Richards, T.E. (2012). Wood Consumption and Analysis of the Bread Baking Process in Wood-Fired Bakery Ovens. *Applied Thermal Engineering*, 47, 63-72

Novaes, E., Kirst, M., Chiang, V., Winter-Sederoff, H., Sederoff, R. (2010). Lignin and Biomass: A Negative Correlation for Wood Formation and Lignin Content in Trees. *Plant Physiology*, 154 (2), 555-561

Rajput, R.K. (2007). *A Textbook of Heat and Mass Transfer*. New Delhi: S. Chand Publishing

Smah, A. C., Joshua, I. O., Enyi, O. S. (2021). Survey on the Use of Energy in Ovens for Baking Bread in North Central Nigeria. *International Journal of Energy and Power Engineering*, 10 (3), 50-56

Salisu, A.T., Barau, A.S., Carr, J.A. (2024). The Forgotten Bread Oven: Local Bakeries, Forests and Energy Transition in Nigeria. *Regional Environmental Change*, 24 (40)

Weather Atlas (2023). Climate and Monthly Weather Forecast Zaria, Nigeria. Retrieved from weather-atlas, available at: https://www.weather-atlas.com/en/nigeria/zaria-climate