

Research Article

Design and Fabrication of a Novel Commercial Baking Oven

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Abstract

This study presents the design and fabrication of a novel wood-fired commercial oven for baking bread. The oven design features an external combustion chamber with heating elements which comprise stainless-steel pipes filled with magnesia starting from the combustion chamber to the 3 oven compartments. Each compartment has 12 heating elements laid under a mild steel sheet metal where the dough mould and its content is placed. Heat loss due to conduction, radiation and convection was prevented by the use of a double wall in both oven and combustion chamber compartments with silica brick and fibre glass respectively, and the oven was fired with wood to bake some dough. Findings showed that maximum temperature attainable by the oven was 700 °C, however, the temperature required for baking bread is between 150 °C and 180 °C and the time was 25 minutes, the quantity of heat generated per time using 10 kg of wood was about 15,088 KJ. Furthermore, the physical appearance of the products was examined to meet consumers' requirement and a total of 400 bread of 180 mm × 120 mm × 80 mm dimensions can be baked at a time. With slight modifications in the oven design, this number can be improved. The oven can be fired with other types of solid biofuels and can be used for metallurgical furnace applications like annealing, tempering and other heat treatments of metals.

Keywords

Oven, Combustion Chamber, Refractories, Bread, Metallurgical Furnace Applications

1. Introduction

Processing of food involves a series of activities embarked upon to ensure the conversion of food from its raw state to a form that is edible and more appealing for human consumption [1]. According to Hager & Morawicki [2] food processing methods include cooking (boiling), frying, roasting, and baking which involve the application of heat from different sources such as burning wood, coal, gas cooker, electric cooker. Baking is one of the oldest food processing techniques that is highly sensitive to heat as the quality and selling price of products significantly depend on the heating process [3]. Baking can also be described as a way of loaf's transformation during a variety of complicated chemical, biochemical, and

physical processes that occur within the product during heating at temperatures above 120 °C. It is an irreversible complex process with diverse application in the food and confectionary industry [4, 5]. During baking, there is a change in the crumb and crust textures of the dough resulting in the formation of a golden brown colour in the product which can be attributed to the high heating temperature and low moisture content [1, 6]. In baking ovens (BOs), the hot air flows over the material either by natural convection or forced by a fan, the convection heat transfer (CVHT) from air, the radiation heat transfer (RDHT) from the oven heating surfaces, and the conduction heat transfer (CDHT) across contact area be-

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tween product and metal surface [7]. In the study by Lyons & Andrea [8], it was stated that ovens are an ancient method of heat treatment. Mondal & Datta [9] described a BO as a fully enclosed thermally insulated chamber use for the heating, baking or drying of a substance whose use can be dated back to 29,000 BC. Prior to the discovery of oven; roasting and boiling pits were the prevalent cooking methods [10]. The quest for optimization of the quality of baked products has led to a continuous research in the design and fabrications of BO [11-14]. The heating process is done by a combination of three forms of heat: by infra-red energy that is radiated from oven walls, by circulating hot air; and by conduction through the baking pan or tray as reported by Ilesanmi & Akinnuli [15]. Oven design is a very critical and significant entity in achieving perfect baking, having understood the physical qualities such as moisture content, surface colour, texture, crumb hardness and porosity of the final baking product, vast knowledge of oven characteristics such as the baking capacity, baking efficiency, weight loss, baking time and optimum baking temperature improves the productivity and energy efficiency of the BO [16, 17]. A designer should also consider oven prices, availability of fuel and affordability, operation modalities, quality of materials and maintenance. The use of electric and solar powered ovens have been shown to have minimal environmental impacts [18-20]. However, the limited knowledge in the fabrication of solar ovens coupled with the irregularity of electricity supply in most developing countries has favoured the use of wood or charcoal fired ovens [21]. The use of wood-fired (WF) BO reduces the stress of procuring petrol, diesel and natural gas at high prices that escalate day by day and almost unavailable since electricity is not stable in Nigeria. It also encourages the drift towards the use of alternative fuel from fossil fuel which would have been used by burners, using wood as fuel to fire the oven will be a succor and sweet relief. The oven will be beneficial to the small and medium scale industries in both the rural and urban areas that are willing to embark on commercial production of bread and other baked products with the intention of increasing productivity thereby creating jobs. The design and fabrication of this oven, therefore becomes significantly imperative.

Therefore, the objective of this paper is to design and fabricate a WF commercial oven for baking with emphasis on infra-red energy that is radiated from oven walls, circulating hot air, conduction through the pipe heating elements and baking trays including the airing system in order enhance efficiency and better output/quality of the finished products.

2. Materials and Methodology

2.1. Heat Theories and Design Calculations

According to Kulla et al. [14], heat transfer (HT) may be defined as the transmission of energy from one region to another as a result of temperature gradient. Heat transfer is as a result of temperature gradient. It takes place by the follow-

ing three modes:

- (1) Conduction.
- (2) Convection.
- (3) Radiation.

Heat transmission in majority of real situations occurs as a result of combustion of the modes of heat transfer in a baking, HT from the burning wood/flame through the heat element to the baking tray and baking space and heat conduction through the oven walls. Heat always flows in the direct of lower temperature.

Conduction

Conduction of heat means heat flow from hotter end to the colder end, i.e, the conduction of heat from the heat furnace or combustion chamber through the heat element to the baking tray and baking space and heat conduction through the oven walls. The greater the temperature difference, the faster the heat will flow. This is determined using Fourier's law of conduction in one dimensional state.

Mathematically it is expressed as

$$Q = KA \frac{dT}{dx} \quad (1)$$

Where:

Q = the rate of heat flows in Kw (KJ/secs),

dT = temperature difference between the surfaces of metal,

dx = thickness of the material (m),

A = area of the section at right angle (m²).

K = thermal conductivity of the material (W/mk),

Convection

Convection is the transfer of energy from one point to another by the motion of a mass of materials between the two different points.

Mathematically, it can be expressed as,

$$Q = LA (T_a - T_b) \quad (2)$$

Where:

L = coefficient of corrective heat transfer,

A = area of surfaces not perpendicular to direction of heat flow,

T_a - T_b = temperature difference.

Radiation

Radiation, an electromagnetic wave such as light and radio waves, is the transfer of heat through space or matter by other means apart from conduction and convection.

It occurs because hot body emits more heat than it receives and a cold body receives more heat than it emits. It requires no medium for propagations and will pass through vacuum. All objects can emit and absorb radiation, and radiation carries energy (W).

Mathematically, it can be expressed as,

$$Q = A\sigma T^4 \quad (3)$$

Where:

Q = heat flux, energy per time,
 A = area of heat flux intensity,
 σ = Stefan Boltzman constant (5.67×10^{-8}) $10/m^2 (K^4)$,
 T = absolute temperature,
Heat Generated in the Oven (Q)
 Heat Generated in the Oven Q , is given by the equation;

$$Q = mC_p\Delta T \quad (4)$$

Where:

Q = Heat generated

m = Total Mass of wood used = 10 kg

C_p = Specific heat capacity of wood = 1.6 kJ/kg K with the wood moisture content between 0% and 25% [22, 23]

Initial oven temperature, $T_1 = 30^\circ\text{C}$

Final oven temperature, $T_2 = 700^\circ\text{C}$

ΔT = Change in temperature

= Final temperature (T_2) – Initial temperature (T_1)

= $700^\circ\text{C} - 30^\circ\text{C} = 670^\circ\text{C}$

= $670 + 273 = 943\text{K}$

But $Q = mC_p\Delta T$

i.e $Q = 10 \times 1.6 \times 943 = 15,088 \text{ KJ}$

2.2. Construction/Fabrication and Description

The method used involved design concept/consideration, design analysis, theory of heat, HT through conduction convection and radiation, design of the oven with Autodesk Inventor, fabrication/welding and painting of the oven as shown in figures 1-5. The oven was designed and fabricated with the use of indigenous materials which are readily available, accessible and affordable according to the conceptual design. The materials used in the fabrication of the oven and the combustion chamber include; galvanized steel sheet metal, mild steel, angle iron, flat bars and square pipes, fibre glass, aluminum foil (for the baking boxes to contain the dough), bricks, clay soil and termite hill, the choice of these materials was based on their availability and affordability. The choice of metal sheet is because it is relatively light. The oven was fabricated and assembled in Ajayi Crowther University, Oyo Bakery; using standard fabrication tools with method of bending, hammering, riveting and welding etc. Figure 4 shows the oven during fabrication and installation and figure 5 shows the installed oven.

The BO consists of the combustion unit/heat source containing the combustion chamber and chimney, baking unit, lagging/insulating unit and temperature monitoring unit. Tools used include; vice, hammer, hacksaw, measuring tape, chisel, anvil, file, try square, arc welding machine while safety devices used are leather apron, industrial boots, nose mask, eye shield, helmet, overalls and first aid kit.

2.3. The Furnace/Combustion Chamber

The oven is designed such that the furnace/combustion

chamber where wood is fired to generate and release the entire heat for baking is located at the back of the oven. It is a separate design but attached to the back of the oven. There is an opening leading to every baking compartment of the oven where heat generated is transferred through the metallic heat element. The combustion chamber has a dimension of 900 mm \times 1440 mm \times 1800 mm (length \times breadth \times height). It is built with clay and termite mud with refractory blocks. It has an opening/gate of 500 mm \times 400 mm (length \times breadth) to accommodate the wood to fire the oven. The wall is built with fired clay bricks for heat retention. A square vent (chimney) of 200 mm and 2400 mm height at 45 degrees is constructed at the top of the combustion chamber for continuous removal of smoke, hot and humid air from the chamber during baking. The top of the chimney is covered temporarily with a thin sheet metal flap to prevent dust and moisture or dew from the atmosphere from entering through to the combustion chamber and a rocket pipe to allow ventilation and passage/release of smoke from the chamber.

2.4. The Oven

The outside of the oven is made up of galvanized steel sheet metal coated with emulsion paint, while the inside is made up of mild sheet. Between the inside and outside of the oven about 10 cm thick is the insulating unit which contains fibre glass for lagging. This unit reduces the transfer of heat energy between objects of different temperatures in thermal contact. The fibre glass is woven into a fabric and pressed to compact round the sides of the oven except the bottom and the rear side in contact with the combustion chamber. The fibre is used because of its properties such as high strength, lightweight, and high thermal shock resistance. The oven design has visible outline edges of 2400 mm \times 1400 mm \times 1800 mm (length \times breadth \times height). The top of the oven is sealed with removable insulated laminated sheets to allow for oven cleaning during maintenance and it is installed as an assembly for easy maintenance, repair and possible modifications. The oven has 3 compartments for baking and each has a dimension of 2300 mm \times 1300 mm \times 300 mm (length \times breadth \times height) with a door and handle for easy opening. In each baking compartment is mild steel sheet metal carrying the metallic box containing the dough to be baked. The internal dimension of the sheet metal oven is 2300 mm \times 1300 mm \times 2 mm (length \times breadth \times thickness) laying on the 12 pieces of 2100 mm long round heat element of diameter 50 mm having magnesia inside as the element. This is solely responsible for conduction of heat from the heat furnace or combustion chamber. This means that the heat element is about 300 mm protruded into the combustion chamber. The dimension of the metal box for the dough is 180 mm \times 120 mm \times 80 mm (length \times breadth \times thickness). With this dimension, the oven can contain about 400 boxes of dough at a time if fully loaded.

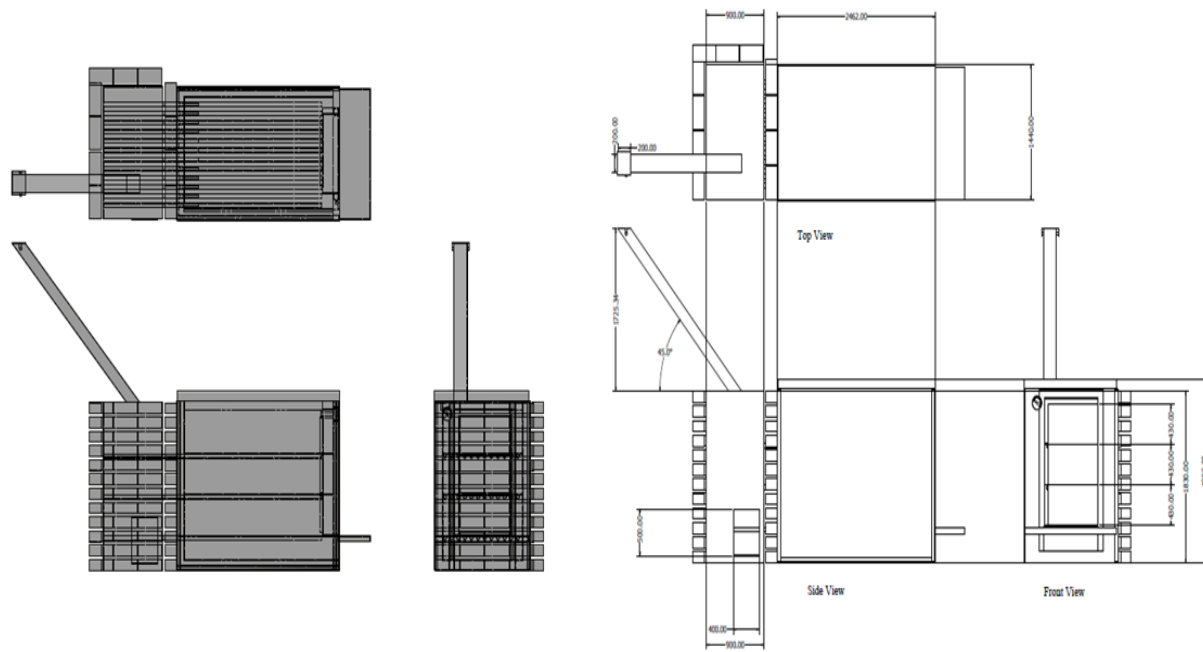


Figure 1. Orthographic projection.

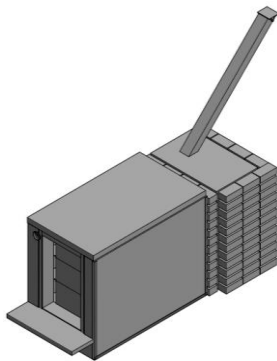


Figure 2. Assembly drawing.

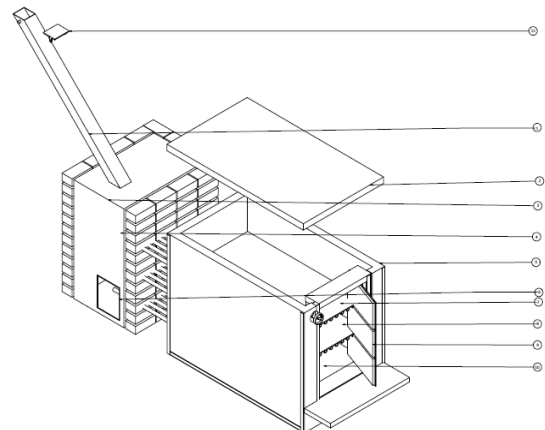


Figure 3. Exploded view.

Table 1. Parts lists.

Part	Name/Description	Material	Number
1	Exhaust	Mild steel of 5mm thickness	1
2	Removable top of Oven chamber	Mild steel of 5mm thickness	1
3	Refractories of combustion chamber	Silica	144
4	Combustion Chamber	Mild steel, termite mud	1
5	Door of Combustion Chamber	Double wall mild steel lagged with fibre glass	1
6	Oven wall	Double wall mild steel lagged with fibre glass	
7, 8, 10	Sheet metal on stainless steel pipes	Mild steel of 2 mm thickness. Stainless steel pipes filled with magnesia as heating element	3 nos sheet metal, 36 nos rods

Part	Name/Description	Material	Number
9	Oven doors	Double wall mild steel lagged with fibre glass	3
11	Exhaust flap	Mild steel of 1 mm thickness	1



Figure 4. The oven during fabrication and installation.



Figure 5. The installed oven.

2.5. Testing of the Oven/ Experimental Procedure

The installed oven was tested by firing to the required

baking temperature (180 degrees celcius). It took about 3 hours of firing with teak wood to achieve this temperature. It took 25 minutes to fully load the oven manually. The upper-most chamber was loaded first, while the lowest chamber was loaded last. A total of 400 boxes of dough measuring 180 mm × 120 mm × 80 mm were loaded. The oven door was shut and allowed to bake for 25 minutes. Total baking time which includes loading time for the first set of bread loaded was 50 minutes. To test the capacity of the oven to bake bread, the dough (unbaked bread) was made following standard baking procedure. The empty bread pans were weighed (m_1), and then the doughs were weighed with the pans (m_2). The mass of the dough (m_3) was then computed as shown in equation 5. The weight of the bread after baking was also taken (m_4). A total of 10 randomly selected samples each of pans, dough with pan and baked bread were weighed. The masses were ascertained using an electronic kitchen measuring scale (Model EK 5055 High Precision). The output/product of the oven (the baked bread) was physically examined for cases of overheating in terms of the coloration.

$$M_3 = m_2 - m_1 \quad (5)$$



Figure 6. The moulds, the dough and the products.

3. Results and Discussions

The result of the testing of the oven capacity to bake bread is presented in [Table 2](#). The average mass of the dough (a pair) with pan is 0.622 g, while the average mass of the pans used is 0.124 g. This implies that the average mass of the dough (unbaked bread) is 0.50 g. Meanwhile the average mass of the baked bread (a pair) is 0.375 g. The average percentage

moisture content lost due to baking is 24.77%. The standard deviation for mass of dough+pan, mass of pan, mass of dough and mass of bread were estimated to be very small which indicate that data points are generally close to the average value. Only the moisture content data produced higher standard deviation values, which can still be considered to be low with respect to the other values.

Table 2. Oven Output Testing (All Masses in Gram).

Sample	1	2	3	4	5	6	7	8	9	10	Average	Standard Deviation
mass of dough + pan	0.63	0.623	0.615	0.612	0.612	0.63	0.623	0.63	0.63	0.615	0.622	0.0074
mass of pan	0.123	0.126	0.123	0.126	0.122	0.123	0.122	0.123	0.126	0.123	0.124	0.0015
Mass of Dough	0.507	0.497	0.492	0.486	0.49	0.507	0.501	0.507	0.504	0.492	0.498	0.0072
mass of bread	0.368	0.366	0.378	0.378	0.366	0.366	0.39	0.368	0.402	0.366	0.375	0.012
Moisture Content	27.416	26.358	23.171	22.222	25.306	27.811	22.156	27.416	20.238	25.61	24.770	2.51



Figure 7. The mould and the oven product being weighed.

The coloration of the bread ranged from light brown to deep brown. None of the bread was returned half-baked or over

baked. The light brown breads were mostly those loaded last, close to the door of the oven while the deep brown breads were those loaded first and very close to the combustion unit. However, both colorations can be sold due to customers' preferences. Some customers want their bread white (light brown) while others want theirs very brown. As such there is no wastage recorded using this oven for baking.

Provisions for further modification

With the current oven arrangement, a total of 405 loaves of bread measuring 18 cm × 12 cm × 8 cm can be baked at once. By creating a metal guide above and below the heating element in the second and topmost oven chamber, this number can be increased by minimum half. Also, in the current oven, the temperature is regulated by either adding or removing woods from the combustion chamber. To this end, the door of the combustion chamber is open during firing which is a major source of heat loss. By adding a blower to the existing design, the combustion unit can be closed and heat loss due to convection can be minimized, temperature can be controlled by the controlling the air flow rate. This will further maximize the energy consumption of the oven. Finally, the maximum temperature of the installed oven is 700 °C which is good enough for annealing treatment of steel and possibility of melting aluminum. This shows that similar oven arrangement with a more compact design can be developed for metallurgical applications.

4. Conclusion

A commercial BO was designed, fabricated and installed in the bakery unit of Ajayi Crowther University, Oyo. As reported by Akinwonmi et al. [24], burners or combustion units gain application in power plants, internal combustion engines, steam plants, ovens, and furnaces.

The oven which comprises a combustion chamber installed outside the bakery building has three oven chambers. HT was due to conduction, radiation, and convection through the use of steel pipes enhanced with magnesia heating element. This was to ensure that the dough being baked had no direct contact with the flames from the combustion unit. Heat loss from the combustion chamber due to radiation was minimized by lagging the walls of the chamber with refractories and the doors with fibre glass. The oven chambers were made of double walled galvanized steel lagged with fibre glass. The oven is unique due to the mode of HT and the fact that other sources of solid fuel can be used for firing such as coal, and solid biofuels in the form of briquettes. The maximum temperature of the oven depends on the mass and type of solid fuel used, however this must be below the fusion temperature of galvanized steel.

Abbreviations

BO	Baking Oven
HT	Heat Transfer

CVHT	Convective Heat Transfer
CDHT	Conductive Heat Transfer
WF	Wood-Fired

Author Contributions

Ademola Samuel Akinwonmi is the sole author. The author read and approved the final manuscript.

Statements and Declarations

The author declares that no funds, grants, or other support were received during the preparation of this manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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