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Development of an improved 100kg/hr Bread Baking Machine

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ABSTRACT: In bread making, baking is a key step in which the raw dough piece is transformed into a light, porous, readily digestible and flavourful product, under the influence of heat. Development of an efficient bread baking machine that is capable of addressing the issue of long baking duration and uneven heating distribution during baking could aid in encouraging indigenous use of the machine by small and medium scale bakeries in Nigeria. This study aimed to develop an improved bread baking machine. The influence of baking temperature (160, 180, 200^{o}C) and machine rack speed (0, 10, 20 rpm) on the bread produced from the improved bread baking machine were evaluated. The baking capacity and efficiency of the improved bread baking machine were found to be 100kgh^{-1} and 92% respectively. The optimum baking time was determined to be 30minutes and was achieved at 200^{o}C baking temperature and 10 rpm rack speed. The machine was designed such that it could be adopted for production of bread and other bakery products.

KEYWORDS: Bread, baking machine, Baking Temperature, Rack speed.

I. INTRODUCTION

The development of food production processes is facilitated by studying the interaction between process design, operational conditions and product characteristics. In bread making, baking is a key step in which the raw dough piece is transformed into a light, porous, readily digestible and flavorful product, under the influence of heat. The baking technology could be regarded as engineering of food structures through formation of correct dough to trap leavening gases and the fixing of these structures by the application of heat [1]. Baking is a complex process that involves heat and mass transfer, physical, chemical and biochemical changes in a product such as volume expansion, evaporation of water, formation of a porous structure, denaturation of protein, gelatinization of starch, crust formation and browning reaction [1]. Mathematically, it can be described as a simultaneous heat and water transport within the product, and with the environment inside the baking chamber [1]. Heat and water transport to the product occurs mainly through natural and forced convection, radiation, conduction from the mold, evaporation of water and condensing steam. Depending upon the product characteristics and oven type, relative contribution of the various mechanisms of heat transfer can be adjusted to achieve a desired quality in the final product. Due to the high energy consumption of the baking process, optimization of oven operating conditions is required to reduce energy consumption as well to improve product quality [1]. Optimization of baking process requires an understanding of the physio-chemical changes involved in the process. During baking, heat is transferred mainly by convection from the heating media and by radiation from oven walls to the product surface followed by conduction to the geometric centre. At the same time moisture diffuses outward to the product surface. The temperature and moisture distribution within the product can be predicted using heat and water diffusion equations [1 and 2]. The vital influence of final product quality includes the rate and amount of heat application, the humidity level in the baking chamber and baking time [1 and 3]. The temperature and air humidity in the baking chamber have a major effect on the rate of heat transfer [3]. It is not always beneficial or desirable to have a maximum rate of heat transfer. However, it is always beneficial to be able to control the rate of heat transfer as this means the process can be controlled and made repeatable. Altering the

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heating rate during baking would potentially vary the kinetics, and extent of disordering of the amylopectin crystals, granule swelling, amylose leaching and, therefore, the effective crumb structure established within the product. These changes would subsequently impact the textural changes occurring in product during storage [4]. Temperature is the fundamental and most obvious factor that affects all three methods of heat transfer (convection, conduction, radiation). It is also the dominating factor in various physical, chemical and biochemical changes during baking: volume expansion, crust formation, inactivation of yeast and enzymatic activities, protein coagulation and gelatinization of starch in dough [5]. Humidity affects the heat transfer rate by allowing water vapour to condense on an object. When water condenses, heat is transferred to the object, and this is known as latent heat of condensation. This energy is comparable to the heat needed to turn the water into steam to start with. When a product is heated directly in a dry environment, it will experience higher temperatures to achieve the same heat transfer as a humid environment using latent heat effects. The level of humidity in the air also affects heat transfer in another specific way. The higher the humidity, the higher the specific heat capacity of a set volume of air (higher capacity to hold more energy). By control of the heat transfer rate and humidity level in the baking chamber, the following benefits could be achieved: products can be heated more effectively, and baking time could be reduced, because the desired core temperature is reached quicker; products can be heated more efficiently, and production costs can be reduced; products can be heated more appropriately, and the yield can be increased; the consistency and repeatability of products could be increased; humidity affects the product performance during baking and ultimately its quality (crust thickness, coloration and crumb formation). Baking involves temperature, moisture content and volume changes that are strongly coupled [6]. Lots of modelling has been developed on baking considering individual phenomena taking place during baking [7]. A dramatic change of physical and chemical property of dough takes place during baking. A qualitative description of mechanical properties such as stress, strain and modulus of elasticity of bread is given by [8]. The air humidity in the oven during baking is known to have a big impact on the oven rise (expansion of the fermented dough at the beginning of baking); however, very studies have documented the impact of the amount of injected steam on the bread and on the crust structure. Two remarkable investigations have been carried out by [9]. In the first study, it was shown that the higher amount of injected steam yielded a higher specific volume and a lower crust crumb ratio; this was explained by the fact that the condensation of moisture (higher amount with higher steaming level) resulted in a delayed fixation of the outer surface of the loaf by drying effect. In turn the loaf had more opportunity to expand and less compression of the crust area by the internal expanding crumb was occurring. It was also observed that a higher steam level yielded a delayed heating (slower heating rate for the centre of the bread at the beginning of baking) due to the fact that, even if the condensation is expected to contribute to an enhanced heat flux, the condensed water has to be evaporated when the surface temperature of the dough passes the dew point temperature. The same author also observed that a higher amount of steam resulted in a darker and glossier crumb, showing a lower moisture permeability level with higher steaming level. [2] studied the effect of baking temperature, baking level, humidity after steaming, air velocity and heat conduction from the hearth on the baking of bread. They developed regression models from the experimental data obtained for baking time (based on surface colour and crumb temperature), baking loss, specific volume, colour and theoretical energy consumption. [10] studied the influence of baking time and temperature on the quality characteristics of par-baked French bread (volume, weight, crust colour, crumb firmness and moisture content). They reported that low temperature and long baking time tend to decrease the crumb firmness of the final bread. Starch gelatinization enthalpies of the bread crumb were similar in breads baked at different initial baking temperatures. An optimized baking process is an appropriate tool for acrylamide reduction. Most of the studies are focused on formulation and product composition, and only few of them have been designed to study systematically the effect of heat and mass transfer and baking conditions on acrylamide formation. The impact of the temperature-time baking regimes was examined in several studies. [11] examined the effect of time and temperature on the formation of acrylamide in bread, flat bread, dry starch systems, and dried rye-based flat bread. In their study the amount of acrylamide was reduced at long baking times, except in the case of bread crust, where the amount of acrylamide increased with both baking time and temperature in the interval tested (180-280°C for 15-45 min).

The ambient temperature has strong linear relationship with the baking temperature. The relationship between the baking temperature and ambient temperature formed the basis for calibrating the baking chamber temperature against the ambient temperature to produce a chart for temperature regulation and this relationship can be used to predict the baking temperature at any given time for a known value of the.

II. METHODOLOGY

The bread baking machine is a compact type of machine that uses the three modes of heat transfer (conduction, convection and radiation) to bake food products. The major materials to be use for the construction of the bread baking machine will be: AISI 304 stainless steel for the construction of both the interior chamber and the exterior chamber, glass fibre will be used for lagging the machine to prevent heat loss from the machine cavity and removable rack to hold food products to be baked. The machine will be design with heat resistance glass door to enhance the ease of monitoring of product during the baking process. Heating element and fan are other key components of the machine. The speed of the fan will be designing such that it varies automatically with the temperature of the heating element. The pressurized air from the fan will pass through the heating element and at the same time been heated before entering into the machine cavity where the baking will take place. A control panel meant for setting baking time, baking temperature and for regulating the speed of rotor that holds the removable rack will also be incorporated. The timer is going to be connected to an alarm system that indicates when the appropriate baking time and the temperature are reached. Also, within the bread baking machine is going to be a thermostat that checks and helps regulate the temperature of the machine. The thermostat will ensure that the temperature within the machine does not exceed the set temperature by the operator.

Design Consideration

The parameters considered in the design of the bread baking machine were selected based on the following factors:

i. Sanitary and hygienic properties of the material: construction material that may come in contact with food must be corrosion resistant, must be inert to the food material under its operating conditions and must be nontoxic. Therefore, AISI 304 stainless steel is going to be used for the inner chamber of the oven while mild steel for the outer chamber.
ii. Availability of the material and cost: the availability of the materials and the overall cost were considered through critical value analysis in material selection, design and production which will make it affordable to users.
iii. Strength and durability of the material: factors such as; strength, durability, stability, vibration were considered in the selection of appropriate materials for the various components of the oven.
iv. The convenience of use during production: The user-friendly interface between the operator and the oven were considered, i.e., ease of operation, convenient handling, the safety of the operator and those within the area of operation of the machine.

Design Calculations.

1) Baking machine and chamber wall:

The dimensions that were used for the design of the machine are shown in the orthographical view in Figure 1.

2.) **Volume of machine baking chamber**:

The baking chamber is the enclosed chamber where the baking takes place and the volume was calculated using Eq. (1) Sanusi et al. (2020).

$$V = BCL \times BCW \times BCH \quad (1)$$

Were,

V is the volume of the baking chamber (mm^3),

BCL is the baking chamber length,

BCW is the baking chamber width and

BCH is the baking chamber height.

Therefore, the volume of the baking chamber (V) is equivalent to 2.903 m^3, given the values of 1.252m, 1.030m and 2.251m for BCL, BCW and BCH respectively.

3.) **Capacity of the machine**:

The capacity of the baking machine is the number of loaves of bread that can be baked in the machine per batch. The capacity of the machine is determined using Eq. (2) Sanusi et al. (2020).

$$\mathbf{CBM} = \frac{\mathbf{SRT}}{\mathbf{SB}} \times \mathbf{NRT} \qquad (2)$$

Where,

CBM is the capacity of the baking machine,

SRT is the size of rack tray

SB is the size of bread, and

NRT is the number of trays

The machine has 2 racks with 10 oven rack tray each.

Therefore, Number of trays = 20

The average mass of bread dough = 0.950 kg

Area of the rack tray = 0.91m (length) × 0.58m (width) = 0.528m^2.

Area of loaf of bread considered = 0.15m (length) × 0.15m (width) = 0.0225m^2.

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Therefore, CBMis equivalent to 469 loaves of bread per batch.

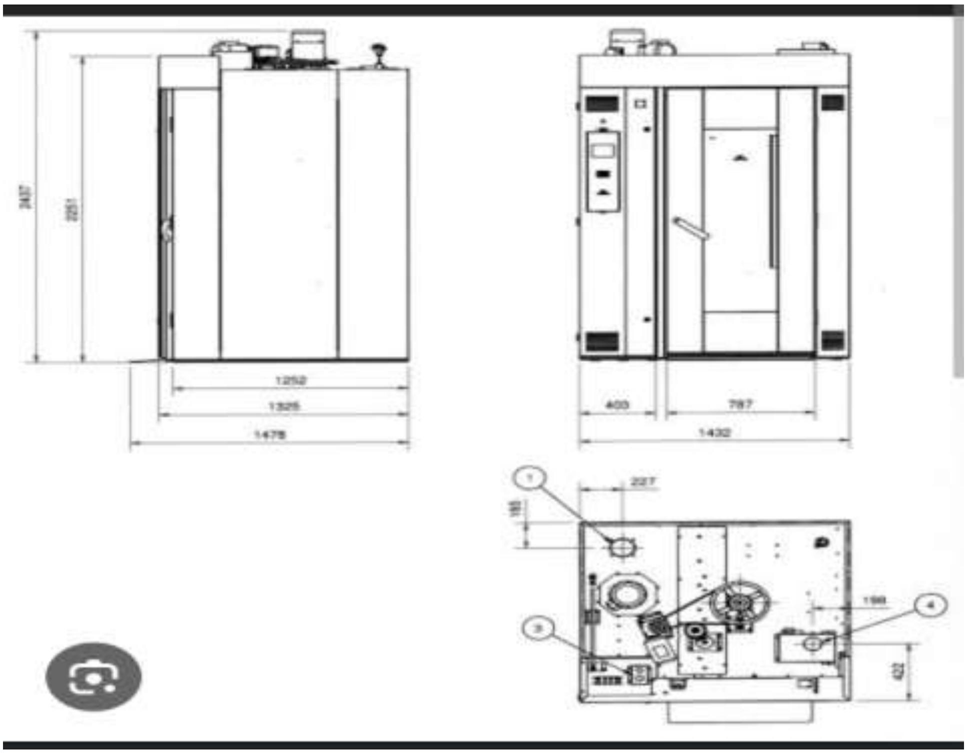

Figure 1: orthographic view of the bread baking machine

4.) Energy requirement:
The heat required will be calculated using Eq. (3) [12].

$Q_H = M_b \times C_b \times T_d$ (3)

Where,

M_b is mass of bread,
C_b is specific heat capacity of bread and
T_d is difference in temperature.

The average oven baking temperature was 200 ºC ≡ 473.15 K; mass of bread is 0.950 kg; Specific heat capacity of bread is 2890 J kg^{-1} K^{-1} according to [13] Oven room temperature is 27 ºC ≡ 300.15 K. Therefore, the quantity of heat required to bake 469 loaves of bread per batch, QH is calculated as 222,761.633 KJ

5.) Airflow required:
The airflow rate (AF) will be calculated using Eq. (4) [14].

$AF = U \times V$ (4)

Were,

U is the air changed (m^3min^{-1}) and
V is the volume of the baking machine.

An air change of 5 m3min-1 was assumed since the value was within the recommended for baking oven design. Given the values of 2.9 m^3 and 5 m3min-1 for V and U respectively, the airflow rate (AF) is 14.5 cfm.

6.) The fan design:
The fan served the purpose of distributing heat by drawing ambient air from the collector to the burner housing and discharging heated air to the baking chamber. The fan horse power (FHP) was calculated using Eq. (5) [15].

$$\mathbf{FHP} = \frac{\mathbf{AF \times PR}}{\mathbf{6320XFE}} \quad (5)$$

Where,

PR is the pressure rise from fan,
FE is the fan efficiency

From literature, most industrial fans have efficiency ranging from 70 - 85%. Assuming a fan with an efficiency of 85% and pressure rise from fan of 1136 mmWg[16]. The fan horse power (FHP) was calculated to be 3.0 Hp, given the values of 14.5 cfm, 1135 mmWg and 0.85 for AF, PR and FE respectively.

Based on the above calculation, an axial flow fan with 3.0 Hp was selected. An axial flow fan was used to ensure proper distribution of air to the oven chamber and for effective heat distribution [17].

7.) Capacity of the heating element:

Power (PHE) of the heating element will be calculated using Eq. 6 [18].

$$\mathbf{PHE} = \frac{\mathbf{E}}{\mathbf{T}} \qquad (6)$$

Where,
PHE is the power of the heating element,
E is the energy and
T is average processing time per dough batch.

Assuming the average processing time per dough batch is 30 min, thus, from Eq. (3) the quantity of heat supplied to the oven chamber is 222,761,633.5 J.

According to [9], 1.2 J/g of energy is needed to gelatinise starch in bread dough, therefore the heat transfer to the dough is equivalent to;

$$\mathbf{HTD} = \mathbf{EGS\ X\ Q_H} \qquad (7)$$

Where,
HTD is heat transfer to the dough and EGS is energy needed to gelatinise the starch in bread dough.
Therefore, the heat transfer to the dough (HTD) was calculated as 267,313,9602 Joules, given the values of 1.2 J/g and 222,761,633.5 J. for EGS and QH respectively. This means that the heating element would supply a minimum of 267,313,9602 Joules of heat energy to the Machine chamber in 30 min.
Thus, PHE = 148,507.76 J/sec. = 148,507.76W = 148.507kW
Thus, power of electrical heating element of 150,000 W or 150 kW was selected.
In order to determine the resistance of the heating element and the current required to operate the machine, Eq. 8 and Eq. 9 were used according to [12].

$$\mathbf{PHE} = \frac{\mathbf{V^2}}{\mathbf{R}} (8)$$

where R is the electrical resistance (Ω), V is voltage supply in Nigeria.
Thus from Eq. (8), the resistance of the heating element, R, is 0.388 Ω, given the values of 240 V and 148,507.76W for V and PHE respectively.
The current required was calculated using Eq. (9).

$$\mathbf{I} = \frac{\mathbf{PHE}}{\mathbf{V}} (9)$$

The current required for the oven was determined to be 618.78 A, given the values of 148,507.76 W and 240 V for PHE and V respectively.

8.) **Selection of Electric Motor**:
The selection of the motor was based on two parameters viz:
i. Rotational speed
ii. Power consumption
The baking machine assumes the use of a 3 amps 3 phase electric motor. [19] approach wasuse to determine the rotational speed as shown in Eq. (10).

$$\mathbf{mgh} = \frac{1}{2}\mathbf{mv^2} \qquad (10)$$

Where,
m is mass of load on the rotor (g),
g is acceleration due to gravity (9.8 ms-2),
h is height of load from the rotor
v is speed of the rotor (ms^{-1}).
From Eq. (10), $v = \sqrt{2gh}$.
Therefore, the speed of the motor was calculated as 1.4 ms^{-1}, given the values of 9.8 ms^{-2} and 0.1 for g and h respectively
For motor power (Pm) consumption determination, Eq. (11) was used [20].

$$P_m = VI\sqrt{3} \qquad (11)$$

Where,
V is the voltage, and I is the current

The motor power consumption was calculated as 257,222.015 W which is equivalent to 257.222 kW, given the values of 240 V, 618.78A for V and I respectively. Therefore, a motor with power consumption of 7 Hp was selected.

Plate 1: Picture of the baking machine

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Performance Evaluation of the Baking machine

Performance evaluation was carried out to determine the functionality and performance characteristics of the baking machine. The performance evaluation characteristics was carried out to establish the optimum baking capacity and baking efficiency.

1.) Baking capacity:
[21] approach was used to determine the baking capacity using Eq. 12.

$$\mathbf{BC} = \frac{\mathbf{MD}}{\mathbf{BT}} \qquad (12)$$

where,
BC is baking capacity;
MD is mass of dough (kg) and
BT is baking time (h)

The baking capacity of the rotary oven was determined by putting into consideration the twenty-three (23) space in the rack compartment (0.58m × 0.91m) and the baking pan for bread dough (0.15m × 0.15m). Nine (469) pieces of bread dough (950 g) each in the baking pan, occupied the rack compartment of the baking machine and the optimum baking time was determined.

2.) Baking efficiency:
The baking efficiency of the rotary oven will be determined by using the ratio of the designed baking time to the actual baking time required to bake a batch of dough to its desired taste, color and texture in the baking machine using Eq. 13 (Okafor et al., 2014).

$$\mathbf{BE} = \frac{\mathbf{DBT}}{\mathbf{ABT}} \qquad (13)$$

where,
BE is baking efficiency,
DBT is designed baking time (min),
ABT is actual baking time (min).

III. CONCLUSION

A baking machine was developed. The performance evaluation of the baking machine showed that the machine has a baking capacity and baking efficiency of 100 kg h^{-1} and 92%, respectively. The optimum machine temperature and machine rack speed were determined and had a significant influence on baking time. The optimum baking time for bread production was achieved in 30 min at 200 °C machine temperature and 10 rpm machine rack speed. The baking machine is recommended for medium and **large-scale** bakeries in developing countries.

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