

DEVELOPMENT OF A DOUGH KNEADING MACHINE WITH THREE DIFFERENT DETACHABLE BEATERS

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ABSTRACT

Dough kneading is an essential operation which enhances the development of gluten that gives bread its structure. Manual dough kneading is laborious, energy-sapping and time consuming, even at a small-scale level of production. This study focused on the development of dough kneading machine and evaluation of the effects of beaters type (elbow, flat and wired) on the physical qualities of bread. The kneader performance was evaluated based on kneading time, kneading efficiency and kneading capacity. The physical properties of the bread in terms of volume, bulk density and weight loss for each beater was measured and analysed statistically at $p < 0.05$. The result shows that kneading time varied significantly based on beater type. Optimum kneading time was achieved at 20 min, 27 min and 35 min for elbow, flat and wired beaters respectively. The optimum kneading efficiency and capacity were found to be 90.13% and 18 kg/h while using elbow beater. From the product evaluation, the beater type had no significant effect at $p < 0.05$ on the volume, bulk density and weight loss of the bread produced using the developed dough kneader. The developed dough kneading machine was efficient for the production of bread when using the elbow beater.

Keywords: Bread, Beaters, Dough, Kneading, Physical properties

1. INTRODUCTION

In bakery industries, kneading is regarded as one of the significant operations that define the mechanical properties of dough, which have a direct effect on the quality of the end product (Rosell and Collar, 2009). To achieve optimal kneading, flour is placed in a vessel of some type which allows the material to be moved and stirred in a desired pattern at the desired speed and torque. The main purpose of the kneading operation is to obtain a homogeneous mixture of the raw and auxiliary materials and at the same time obtain dough with viscous-elastic structure and properties (Canja *et al.*, 2014).

Kneading of dough enhances development of gluten, the protein found mainly in wheat flour. Kneading incorporates air and breaks the air pocket to form viscous-elastic material. This mechanical operation stretches the gluten into sheets that trap the CO₂ as the dough expands (Hwang and Gunasekaran, 2001). It also helps to equalize temperature throughout the dough mass and cause the subdivision of gas bubbles formed during fermentation to give uniformity and fineness to the grains (Dahiru *et al.*, 2007).

In Nigeria, large-scale bakeries adopted conventional dough kneaders such as vertical bowl and planetary kneaders with dough hook or

spiral blade. These kneaders are powered with electric motors of higher capacities and more importantly, due to irregular supply of electricity, size and high power consumption, such equipment could not be acquired by small-scale bakers. This has resulted to the use of manual kneading of dough by small-scale bakers which is more labour intensive, has high risk of cross-contamination and low production rate to meet the challenges of high demand (Owolabi *et al.*, 2017).

There is a need to develop a dough kneading machine of higher economy comparative advantage, running with a lower capacity of electric motor which can be propelled using a two-stroke engine, even at the rural area for small-scale bakers. In this study, a small-scale dough kneading machine was developed with an adjustable speed to improve control and three detachable beaters so that the machine can knead dough for different bakery products.

The existence of the dough kneading machine has been developed in ancient Rome since 18th century, with many modifications through patent after patent into the present century as Science and Technology advance (Owolabi *et al.*, 2017). Previous researchers such as Chikelu *et al.* (2015) and Okafor (2017) had reported on development and modifications of dough mixers, however, little has been reported on the development of a kneading machine with detachable beaters. The development of a dough kneading machine with three detachable beaters will make it versatile for different bakery products. Hence, the objective of this study was to develop a dough kneading

machine with three detachable beaters. Also, to evaluate the effect of beater type on the physical qualities which include volume, bulk density and weight loss on bread produced from the dough kneading machine.

2. MATERIALS AND METHODS

2.1 Design Factors

Different design factors were taken into consideration, as follows: size of mixing bowl, i.e., the dimensions: circumference = 1220 mm, height = 280 mm. Materials for the components of the dough kneading machine are selected based on food compatibility, availability, sustainability for working conditions in service, and cost. Some of the important properties of the materials that influenced their selection are strength, durability, resistance to corrosion, inertness to food and machinability. Materials to be used are as follows: food-grade stainless steel for the mixing bowl, beater and shaft while mild steel for the support structure and iron and mild steel for bolts and nuts.

2.2 Design Consideration

2.2.1 Design of mixing vessel

The design of the mixing vessel was based on the maximum capacity of the dough the vessel can contain in a single operation. The circumference (C) of the vessel was taken as 1.22 m, height was 0.28 m and height of the cylindrical bowl was 0.24 m, thus the diameter of the vessel (D) was calculated from equation 1.

$$D = \frac{C}{\pi} = \frac{1.22}{\pi} = 0.388 \text{ m} \quad (1)$$

The total volume of the vessel (v) is the sum of

the cylinder volume and the hemisphere volume.

Therefore radius (r), $r = \frac{0.388}{2} = 0.194 \text{ m}$

$$v = \pi r^2 h + \frac{2}{3} \pi r^3 = 0.0436 \text{ m}^3 \quad (2)$$

The density of dough is given as 593 kg/m³

$$\text{Thus, } m = \rho \times v = 26 \text{ kg} \quad (3)$$

where, m is mass of dough, ρ is density of dough and v is total volume of the vessel.

Therefore, based on the above calculation the mixing vessel can contain maximum of 26 kg of dough.

2.2.2 Selection of electric motor

The selection of the electric motor is based on the following parameters; horse power, rotational speed and phase. To determine the power required to rotate the spindle through the dough, two energies are considered; the potential energy (Mgh) of the ingredients contained in the mixing bowl and the kinetic energy $\left(\frac{1}{2}MV^2\right)$ of the beater mixing the ingredients inside the bowl. Where, M = mass of flour (kg), g = acceleration due to gravity (m/s²), h = height of the mixing vessel (m) and V = speed of the beater (m/s)

The resistance offered by the flour to be kneaded must be overcome by the driving or mixing energy of the beater. Therefore, the potential energy of the flour to be kneaded must be equal to or less than the kinetic energy of the beater.

Potential energy = Kinetic energy

$$Mgh = \frac{1}{2}MV^2 \quad (4)$$

$$V = \sqrt{2gh} = 2.34 \text{ m/s} \quad (5)$$

$$V_s = \frac{\pi D_s N}{60} \quad (\text{Faires, 1965; McCable et al., 1985})$$

$$(6)$$

D_s , Diameter of the vessel = 0.388 m (eqn. 1)

N = Speed of the beater in rpm

V_s , Beater speed = 2.34 m/s (from eqn. 5)

From eqn. 6,

$$N = \frac{60V_s}{\pi D_s} = 115.18 \text{ rpm} \quad (7)$$

$$F = \frac{mv^2}{r} \quad (8)$$

F = Force (N)

M = Mass of the dough (kg)

g = Acceleration due to gravity (m/s²)

$$F = \frac{26 \times 2.34^2}{0.194} = 733.84 \text{ N}$$

Maximum Power required in kneading the ingredients,

$$P = FV = 1717.19 \text{ W} \quad (9)$$

Power = 2.30 hp

Therefore, a single phase, 2.5 hp electric motor was selected for maximum efficiency.

2.2.3 Design of mixer beater and shaft

Sufficient mechanical strength is the first design criteria for a mixer beater and shaft. To avoid fatigue failure, the stresses in the shaft should be kept to levels well below the yield point, where a shaft might bend or twist. In the kneader, when the dough beater and shaft are loaded, the shaft would be subjected to twisting moment or torque and bending moment is neglected since the shaft was mounted vertically (David, 2010). Besides the forces that resist the rotating beater, moving fluid creates random hydraulic forces that act perpendicular to the shaft. These create bending moment on the shaft (Dickey and Fasano, 2004).

The diameter of the beater was first determined;

$$\text{Diameter of the beater } D_s = D_v - C_1 - C_2 \quad (10)$$

where; D_v = diameter of the vessel = 0.38 m
(From eqn. 1)

C_1 and C_2 = Clearance of blade from sides of the vessel wall

C_1 = 0.10 m (assumed)

C_2 = 0.05 m (assumed).

Then, the diameter of the shaft was determined as follow;

Vessel diameter (D_v) = 0.38 m (Eqn. 1)

$$D_s = 0.38 - 0.10 - 0.05 = 0.23$$

Diameter of the beater = 0.23 m

$$M = \sum \frac{0.048 P_i L_i F_{Hi}}{N D_i} \quad (\text{David, 2009}) \quad (11)$$

M = Bending Moment (Nm)

P_i , Power required to mix = 573.89 W (eqn. 9)

L_i = Shaft length = 0.155 m (assumed)

N = Rotational speed of the beater = 115.18 rpm
(from eqn. 7)

D_i = Diameter of the beater = 0.23 m (eqn. 10)

F_{Hi} = Hydraulic force factor = 3 (David, 2009)

$$M = \sum \frac{0.048 \times 573.89 \times 0.155 \times 3}{115.18 \times 0.23} = 0.484 \text{ Nm}$$

The bending moment caused by the hydraulic forces is too small. So, it is negligible.

Therefore, the shaft would only be subjected to twisting moment

$$\text{Torque (T)} = \frac{60P}{2\pi N} \quad (\text{Khurmi and Gupta, 2008}) \quad (12)$$

T = Twisting moment or torque acting on the shaft
 P is power required to mix = 573.89 W
(from eqn. 9)

N , Rotational speed = 115.18 rpm (from eqn. 7)

$$T = \frac{60 \times 573.89}{2\pi \times 115.18} = 47.58 \text{ Nm}$$

Diameter of Shaft;

$$T = \frac{\pi}{16} \times \tau \times d^3 \quad (\text{Khurmi, and Gupta, 2008}) \quad (13)$$

$$\text{Therefore, } d = \sqrt[3]{\left(\frac{16 \times T}{\pi \times \tau}\right)}$$

d = Diameter of shaft

T = Twisting moment = 47.58 Nm (from eqn. 12)

τ = Torsional shear stress of stainless steel (304L)
= $35.2 \times 10^6 \text{ N/m}^2$ (David, 2009)

$$d = \sqrt[3]{\left(\frac{16 \times 47.58}{\pi \times 35.2 \times 10^6}\right)} = 0.019 \text{ m}$$

Therefore, diameter of shaft = 0.019 m

2.2.4 Design of the support structure

At a more practical level, torque and bending loads must be known or specified to design a mounting structure for the mixer. Whether the mixer is supported from beams or on a tank nozzle, the support must be sufficiently strong and rigid. Strength is an obvious requirement; however, stiffness is usually found to be a more restrictive parameter. A support structure may not break with a little flexibility, but only minor movement at the support can cause a long mixer shaft to move significantly. To prevent the mixer from moving too much, the support is designed for higher loads, thus providing sufficient stiffness. Designing the support for 2.5 times the torsional load and 3.0 times the bending load will provide sufficient stiffness for the mixer mounting (David, 2009).

Torsional load = 47.58 Nm (from eqn. 12)

Bending load = 0.484 Nm (from eqn. 13)

A supporting structure = $(2.5 \times 47.58) + (3.0 \times 0.484)$

Total load for support structure = 120.40 Nm

2.3 Dough kneading machine working principle

The exploded view of the dough kneading machine is presented in Figure 1. The dough kneading machine operation is initiated by two motor drives. The motion which in-turn is transmitted to the dough beater via the shaft, the motion is simultaneously transmitted to the mixing bowl through its base connected to the other drive. The recipe mix is fed into the mixing bowl, the dough beater then carries out the kneading action through its rotational motion in a counteract directions. The speed of the mixing bowl and beater can be varied from 15 to 115 rpm. Figure 2 shows the photographic view of the machine and dough beaters.

2.4 Determination of Kneading Machine Performance

Performance test was carried out to determine functionality and performance characteristics of the dough kneading machine. This is because establishing the performance characteristics of a system before putting it to use is important and it gives a better understanding of the machine and an edge in safeguarding it (Mathew *et al.*, 1997; Uhummwangho *et al.*, 2003). For the dough kneading machine, two performance tests were carried out on the machine; they included free rotation test and load test. Also, the performance evaluation of the dough kneader was further determined by establishing the optimum kneading time for each beater, kneading efficiency and capacity of kneader using Equations 14-15.

$$KC = \frac{M}{t} \quad (14)$$

where, KC is kneading capacity, m is mass of dough, t is kneading time.

Kneading efficiency is determined by using relation

$$KE = \frac{OMC}{DMC} \quad (15) \text{ (Chikelu *et al.*, 2015)}$$

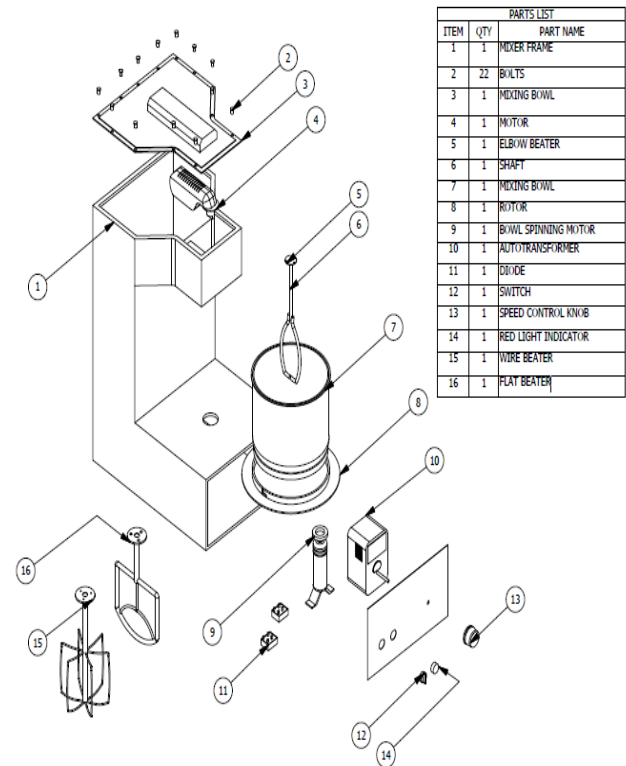


Figure 1: Exploded view of the dough kneading machine

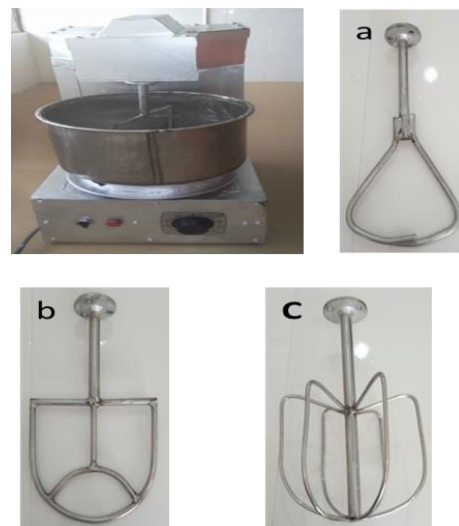


Figure 2: Photographic view of the developed machine and photographic view of the developed dough beaters (a- Elbow beater, b- Flat beater, c- Wired beater).

where, KE is kneading efficiency, OMC is output mixing capacity and DMC is designed mixing capacity.

2.5 Bread dough preparation

The recipe used for bread dough preparation consisted of wheat flour (57.12%), water (29.02%), sugar (7.65%), salt (0.86%), oil (0.96%), margarine (1.87%), milk (1.83%) and baker's yeast (0.69%). For each beater, 9 kg of the recipe were mix and replicated three times. The kneading process was terminated after windowpane and poke test gave a positive result and smooth dough was achieved. After kneading, dough was given about 10 min intermediate proofing at 32°C followed by moulding on a work table. Dough was then placed in baking pans and proofed in a fabricated proofer of the Department of Food Engineering, University of Ilorin, for 45 min at 40°C and baked in a fabricated rotary oven of the Department of Food Engineering, University of Ilorin at 180°C for about 30 min. Loaves were cooled at ambient temperature. Parameters such as length, width and height were measured using a digital vernier caliper (Model AD-5765-100, China) having a resolution of 0.01 mm. Volume, density and weight loss of the bread produced from the newly developed dough kneader was determined using the following mathematical equations 16 - 18;

$$v_b = l \times b \times h_b \quad (16)$$

$$\rho = \frac{m_b}{v_b} \quad (17)$$

$$WL = m_b - m_d \quad (18)$$

where, v_b is the volume of the bread, l is length, b is breadth and h_b is height of the bread, ρ is

density, m_b is mass of bread, WL is weight loss, m_d is mass of dough

2.6 Statistical Analysis

All determinations were performed in triplicates ($n=3$) and subjected to One-way Analysis of Variance (ANOVA) and means were separated using Duncan's Multiple-Range Test (DMRT) at $p < 0.05$. All analysis was done using SPSS 20.0 software package (SPSS, Inc., UK).

3. RESULTS AND DISCUSSION

3.1 Dough kneading machine performance tests

For the free rotation test, the machine was set to run without load and it was observed that there were no abnormalities, noise or vibration which may be as a result of improper alignment during fabrication and assembling of the machine working components. During the load test, recipe mix was fed into the mixing bowl and then rotated by the beater such that the dough was picked and kneaded. This was done until satisfactory bread dough attributes were achieved in terms of tenacity, elasticity, extensibility and non-stickiness. The load test was done using slow mixing and fast mixing at 30 to 100 rpm for 6 kg of dough using elbow beater, flat beater and wired beater. According to Owolabi *et al.* (2017), optimum agitator speed of 100 rpm is required to bread dough formation using a motorized dough kneading machine. The optimum kneading time for bread dough formation were 20 min, 27 min and 35 min for elbow, flat and wired beaters respectively as shown in Table 1. The kneading efficiency of the newly developed dough kneading machine varied relatively with the use of

different beaters as shown in Table 1. The maximum kneading efficiency of the kneading machine was 90.13% which occurred when using the elbow beater while the minimum kneading efficiency was 51.70% which occurred while using the wired beater. This is due to the reduction in the kneading time as shown in Table 1. Longer kneading time causes the dough to get too warm and ferment too quickly causing lack of flavour and break in molecular bonds of the gluten network. Therefore, longer kneading time is undesirable. Therefore, the elbow beater has the best optimum efficiency (90.13%) because of its ability to achieve a satisfactory dough formation within a shorter duration of 20 min. The dough kneading machine was designed for 20 kg/h. However, during testing, 6 kg of dough was used and the optimum dough development by the elbow beater (most efficient) was achieved in 20 min. Hence, the optimum kneading capacity was found to be 18 kg/h.

Table 1: Effect of beater type on kneading time and efficiency

Beater Types	Kneading Time (min)	Kneading Efficiency (%)
Elbow	20.0±1.0 ^c	90.13±4.50 ^c
Flat	27.0±2.0 ^b	66.93±4.95 ^b
Wired	35.0±3.0 ^a	51.70±4.46 ^a

*Mean values bearing the same superscript do not differ significantly at $p < 0.05$

3.2 Effect of Beater Type on Bread Produced

3.2.1. Bread volume

Volume (cm^3) is considered as an important bread characteristic since it provides quantitative

information of the bread-making process performance (Mondal and Datta, 2008; Maktouf *et al.*, 2016) and leavened gas retention capability from kneading within the dough mass (Onyango, 2009; Purna Garimella, 2011). Manuel *et al.* (2013), reported that the mixer arm used affected the bread volume. Table 2 shows the effect of beater type on bread volume produced using the newly developed dough kneading machine. Maximum volume ($2580.0 \pm 293.6 \text{ cm}^3$) occurred when using the wired beater while the minimum occurred with the flat beater ($2535.0 \pm 68.7 \text{ cm}^3$). The results of the statistical analysis indicated that the beater type had no significant effect ($p < 0.05$) on volume of the bread. This could be due to proofing that occurred after kneading. According to Tlapale-Valdivia *et al.* (2010), bread volume can be affected by the proofing condition.

Table 2: Effect of beater type on physical properties of bread

Beater Type	Volume (cm^3)	Bulk Density (g/cm^3)	Weight Loss (g)
Elbow	2572.5 ± 46.8^a	0.368 ± 0.009^a	24.67 ± 5.03^a
Flat	2535.0 ± 68.7^a	0.369 ± 0.010^a	24.33 ± 2.08^a
Wired	2580.0 ± 293.6^a	0.362 ± 0.044^a	28.67 ± 1.15^a

*Mean values bearing the same superscript do not differ significantly at $p < 0.05$

3.2.2. Bread density

Density (g/cm^3) of baked products such as bread, the production of which is a significant commercial concern, is affected by the way the dough rheology during kneading and vapour content change during the baking process (Jefferson *et al.* 2007). Calderon-Dominguez *et al.* (2004), reported that density is affected by dough

extensibility which is a function of the cross-links between gluten proteins (Lee *et al.*, 2003), these cross-links is as a result of the kneading time (Charun *et al.*, 2000). Thus, variations in kneading time would affect the density of the bread. Table 2 shows the effect of beater types on the density of the bread produced using the developed dough kneading machine. Maximum density ($0.369 \pm 0.010 \text{ g/cm}^3$) occurred when using the flat beater while the minimum ($0.362 \pm 0.044 \text{ g/cm}^3$) occurred with the wired beater. The results of the statistical analysis indicated that the beater type had no significant effect ($p < 0.05$) on density of the bread. This result contradict the findings of Lee *et al.* (2003), however, the non-significant could be due to the fermentation process as Liao *et al.* (1998), reported that during fermentation, there are changes in extensographic dough properties which affect density.

3.2.3. Weight loss

The weight loss of bread is related to the formation of gluten during kneading, so that the dough is ready to hold CO_2 gas from fermentation activity (Srirejeki *et al.*, 2018). Table 2 shows the effect of the beater types on weight loss of the bread produced using the developed dough kneading machine. Maximum weight loss occurred when using the wired beater ($28.67 \pm 1.15 \text{ g}$) while the minimum occurred with the flat beater ($24.33 \pm 2.08 \text{ g}$). The results of the statistical analysis indicated that the beater type had no significant effect ($p < 0.05$) on weight loss of the bread. This could be due to the proofing and baking conditions as (Bakare *et al.*, 2016),

reported that weight losses occur during proofing due to the utilization of soluble sugar by yeast during fermentation and evaporation of moisture during baking.

4. CONCLUSIONS

A small scale dough kneading machine for the production of bread was successfully designed, developed and evaluated. The performance evaluation of the dough kneading machine showed that there was a considerable decrease in kneading time with the use of different beaters. The optimum efficiency for the kneading of bread dough was found to be 90.13% and it occurred while using elbow beater with kneading capacity of 18 kg/h. From the evaluation of the physical properties of the bread, it was deduced that the beater types did not affect the bread properties. The performance of the flat, wire and elbow beaters should be evaluated for other bakery products such as batter for cake and pastries doughs. The dough kneading machine is strongly recommended for small and medium scale bakeries.

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