OPTIMIZATION OF OPERATION PARAMETERS OF A DEVELOPED DOUGH MIXER

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ABSTRACT

A mixer is essentially required for homogenizing flour and other ingredients in the bakery industry. In this research, a dough mixer was developed using a 10.5% chromium stainless-steel and its performance evaluated based on the machine parameters. The shaft speed (250−350 rpm), agitator geometry angle (45º, 60º and 90º) and number of blades (type A-5, type B-4 and type C-3) were considered as the machine parameters. The Effective mix proportion (EMP) was determined as the performance index. A Split-Plot Optimal Design was used to determine the desired variables for maximum EMP. Results show that the EMP decreases with an increase in the agitator geometry angle, irrespective of the speed of the mixing shaft. A critical behavior of the mixer was obtained at 300rpm, which indicates the homogeneous phase change stage in the mixing process. Again, the mixer performance was higher for the agitator with 5 blades and lower for the 3 blades agitator. The optimum EMP occurred for type C-3 blades, 60º geometry angle at 250 rpm with 98% desirability. These can be considered as the best configurations for a large-scale practice.

Keywords: Design, Fabrication, Performance, Optimization, Dough

1. Introduction

Dough is a thick, malleable, and elastic pastry, which is made from a mixture of flour, water and other ingredients (Jongen *et al.*, 2003). The flours are usually produced from a wide variety of cereals, including wheat, rice and maize. The process of making and shaping dough is a precursor to making various kinds of foodstuffs, particularly breads and bread-based items, but also including biscuits, cakes, cookies, flatbreads, noodles, pasta, pizza, piecrusts, and many similar items (Ktenioudaki *et al.*, 2010). The mixing procedure in the dough formulation usually require rigorous and sophisticated mechanical operations to produce homogeneous product. Work input and mixing intensity are two critical factors for optimal dough formulation. Work input is the energy required to mix the dough until a peak in the development curve is reached; whereas the mixing intensity is the rate at which the dough is mixed (Alara *et al.*, 2001). Both should be above a minimum critical value and vary with the flour properties and with the type of mixer used (Jongen *et al.*, 2003; Ktenioudaki *et al.*, 2010).

Mixing is the physical or chemical combination of two or more dissimilar particles of a material. The final product of a mixture is likely to attain a desired level of uniformity. The mixing operation is the most critical aspect of the process of a product homogenization and the dough development. The homogenization may lead to a reduction in the concentration of the product or temperature gradients within the mixing vessel (Rajasekaran and Kumar, 2014). The performance of a mixing machine can be measured in terms of the effective mix proportion. In fluid mixing, the effective mix proportion may be visualized as an agitation of the molecules or particles in a confined space within the fluid system. This often cause an increase in the contact area of fluid particles and a decrease in the particle distance thereby causing the material to mix proportionately (Evans and Liepmann, 1997; Bharatkumar *et al.*, 2001). This parameter describes the ability of the machine to perform the mixing operation with minimal material loss (Fall *et al.*, 2008). In mixer design analysis, factors such as geometry of the mixing tank, impeller type, speed of the mixing shaft and the nature of the mixture are critical to the performance of the technology. Different materials require different types of impellers and tank geometries to achieve the desired product quality. The flow field and mixing process even in a simple vessel may be very complex. This may be associated with the rotating impeller blades which interact with the agitator to generates a complex flow (Gaikwad *et al.*, 2016). The other parameters like impeller clearance from the tank bottom, proximity of the vessel walls, baffle length may also affect the general flow pattern and hence mixing (Karaagac and Toygar, 2006; Xing-hua and Zhang, 2000).

Dynamic process of dough development causes low correlations between the dough rheological parameters (development time, dough stability, softness) obtained from different mixers (Robinson and Cleary, 2012). The empirical dough mixers, like farinograph or mixograph, have been developed to control the testing conditions at laboratory scale but these do not exert identical mixing actions in comparison with the industrial mixers (Robinson and Cleary, 2012; Okafor, 2015; Park *et al.*, 2014). Although, modern dough mixers are equipped with sophisticated gargets that ensure easier mixing operations. But these do not ensure efficient and effective utilization of flour in the process and are mainly suitable for industrial applications. Thus, efforts to design dough mixers cannot be overemphasized since there is no single mixer design that can universally satisfy all mixing requirements (Vincent, 1996). Although, the design and performance of various types of dough mixing machines have been reported (Okafor, 2015; Ajibola and Ibrahim, 2010; Liu *et al.*, 2016), the authors did not consider the effects of the speed, agitator geometry angle and the number of blades and their interactions on the effective mix proportion in their analysis. Also, the available mixers are characterized with inadequate strength to handle the dough in its most viscous condition and reduced output and require large amount of mechanical energy to operate (Ajibola and Ibrahim, 2010). Thus, the previous designs are not reliable especially with respect to process control and materials balance analysis or automation. There is therefore the need to design and fabricate a dough mixer, and to carryout optimization on the operational parameters to ascertain the right combination for effective material and machine usage. The objective of this research was to develop and optimize the operational parameters (speed of the shaft, impeller geometry and number of blades) as it affects the effective mix proportion of a dough mixer.

2. Materials and methods

2.1 Materials selection and design consideration

In this study, the materials used for the construction of the dough mixer were selected based on their strength and chemical inertness for food contact. A chromium-nickel stainless steel (10.5 % chromium) was used because of its polished surface and its ability to withstand ordinary corrosion. A scraper made of food grade plastic was used for cleaning. The mixer was designed to process 10 kg of a mixture of flour, water, and ingredient per minute. This was necessary to eliminate waiting and idle times where dough might stand for too long and becomes gassy. The elastic modulus of the agitator material was 200 GPa. A value of 108 mm shorter twisting arm length and 122 mm longer twisting arm length were assumed for a thorough mixing of the dough in the bowl (Asiri, 2012). The electric motor size was selected based on the power requirement and the speed to match the intensity, viscosity and strength of the resulting dough for a batch operation.

2.2 Description of the dough mixer

The components (exploded view) of the dough mixing machine is shown in Figure 1. The machine consists of a mixing bowl for the mixing operation, electric motor to provide power for the machine operation, agitator for homogenizing the food constituents, straight shaft for power transmission, a frame, and bearings for support. The agitator vanes size was made thick to boost the torque and distribute the energy evenly throughout the mixing vessel. The rotation of the shaft creates the stirring effect of the agitator. Three speed levels are achieved from the electric motor, namely low (250 rpm), medium (300 rpm) and high (350 rpm). Three different agitators with variable angles (45^o, 60^o and 90^o) were coupled separately to the mixing shaft of the machine. The effect of each configuration on the homogeneity of the dough was determined.

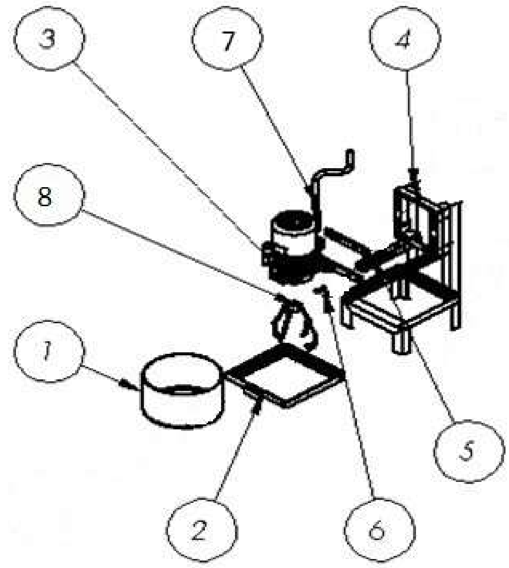

Figure 1. Exploded view of the dough mixer (1-mixing bowl, 2-bowl base, 3-electric motor, 4-frame, 5-slider, 6-bolt and nut, 7-torque lever, 8-Agitator)

2.3 Design analysis

Mixing bowl: The mixing bowl is the container that accommodates the dough in the machine as shown in Figure 3. The design of the bowl was carried out by considering the expected quantity of the dough per time, the design height and width of the frame, and the shape and size of the agitator. In designing for a mixer capable of mixing 10 kg of blend flour per minute, at 16,942Nm^{-2} mixing pressure, 350 rpm impeller speed, 1258 kgm^{-3} dough density is used in dough volume calculation (Kennard, 2012). Thus, the volume of the mixing bowl was computed using equation (1).

$$V_b = 2.5\ m_d/\rho_d \quad (1)$$

where,

V_b = volume of bowl (m^3),

m_d = mass blend or composite flour (kg)

ρ_d = dough density (kgm^{-3}).

Circular shaft: The shaft was used to transmit power and torque from the prime mover to the agitator. This is also facilitated using a gear train mechanism. An internal spur gear meshed with an external spur converts the rotational motion from the electric motor to a circular trajectory. The effect of the output motion was therefore a revolving twist on the agitator. The size of the shaft diameter was computed using equation (2) (Khurmi and Gupta, 2008; Fadeyibi and Ajao, 2020).

$$D_f{}^3 = \frac{16}{\pi S_u}(\sqrt{(K_t M_t)^2 + (K_b M_b)^2} \quad (2)$$

where,
D_f = Shaft diameter (m)
M_b = Bending Moment (Nm)
M_t = Torsional moment (Nm)
K_b = Combined shock and fatigue factor for bending moment (1.5)
K_t = Combine shock and fatigue factor for torsional moment (1.0)

S_u = Allowable for shaft with keyway is 40 MN/m^2

Blade thickness: Blade thickness design is obviously essential for an effective mixing operation. The blades must be thick enough to handle fluctuating loads without bending or breaking. The minimum blade thickness was computed using equation (3) (Asiri, 2012).

$$\delta = 0.98\sqrt{(0.5Pf_lD - 0.5D)/0.5DW\sigma_b N n_b\, f_l \sin\alpha)} \quad (3)$$

Where,
δ = minimum blade thickness (m)
f_l = location fraction for PBT equal to 0.8,
P = weight of blade material (6 N)

N = speed (250, 300 and 350 rpm)
D = shaft diameter (m)
W = width of the blade (assumed 20 mm),
n_b = Number of blades
σ_b = blade allowable stress which is equal to 40×10^6 N/m^2
$\boldsymbol{\alpha}$ = blade geometry (45, 60 and 90°).

Power requirement: Electric motor drives a gear train that creates the rotation and revolution for the agitator. The power loss was minimally reduced by incorporating a gear system rather than the use of a belt and pulley. The gear was used to vary the speed of the rotating shaft as 250, 300 and 350 rpm. The capacity of the electric motor was affected by the weight of agitator and bearings, volume and density of dough mixed, shear stress on the bowl walls, viscosity of the dough mixture, torque required for effective mixing and angular velocity of the agitator. The power input was computed from equation (4), which relates the efficiency of the reducing gear, input power and the output power in the mixing process (Karaagac and Toygar, 2006). By solving equation (4) for *P* it was found that P = 1739.31 W or 1.739 kW, and this gives 2.33 hp. Thus, accounting for power losses to due friction and other sources, we therefore selected 3 hp single phase electric motor to power the dough mixer.

$$\boldsymbol{\eta = \frac{P_i}{P} \times 100\%} \qquad (4)$$

but, the input power was

$$\boldsymbol{P_i = VAcos\,\emptyset}$$

where,

P_i = power input (W),
P = power output (W)
V = voltage drawn from electric motor (230 Volt) (Karaagac and Toygar, 2006).
A = current drawn from electric motor (8.2 A) (Karaagac and Toygar, 2006).
$\mathbf{cos}\,\emptyset$ = power factor drawn from the electric motor (0.83) (Karaagac and Toygar, 2006).
$\boldsymbol{\eta}$ = efficiency of the reducing gear (assumed 90%)

Torque applied to the shaft: The torque generated from each agitator was computed using equation (5) (Gaikward *et al.*, 2016; Karaagac and Toygar, 2006; Khurmi and Gupta, 2008). By solving equation (5) for T_m it was found that the torques of the driven spindle shaft were 59.79, 49.82 and 42.70 Nm with respect to the mixing speeds of 250, 300 and 350 rpm, respectively.

$$\boldsymbol{T_m = \frac{P_i}{2\pi N_m}} \qquad (5)$$

where,

P_i = input power (1.57 kW),

N_m = mixing speed (250, 300 and 350 rpm)

T_m = torque of the driven spindle shaft (Nm)

Agitator: The agitator was used to propel the dough mixture in motion and stirring. The agitators consist of an impeller rotor located in a conduit attached to a shaft. In this study, the angular spacing of the agitator vane was varied into three geometrical orientations, namely; 90°, 60° and 45° as shown in Figure 2. The inertia moments of the cross section of the impeller top structure acting about the *x* and *z* direction were computed using equations (6) and (7), respectively. Also, the inertia moment acting on the impeller shaft acting about the *x* and *z* axes of rotation was computed using equation (8) (Karaagac and Toygar, 2006).

$$I_x = 2\frac{1}{8}(2\alpha - \sin 2\alpha)(r_1{}^4 - r_2{}^4) \qquad (6)$$

$$I_z = 2\frac{1}{8}(2\alpha + \sin 2\alpha)(r_1{}^4 - r_2{}^4) \qquad (7)$$

$$I_{xs} = I_{zs} = \frac{\pi d^4}{64} \qquad (8)$$

where,

I_x and I_z are the inertia moments on the cross section of the top structure acting about the *x* and *z* direction;

I_{xs} and I_{zs} are the inertia moments on the cross section of the

α = blade geometry (45, 60, and 90°)

r_1 and r_2 are longer and shorter arm lengths (122 mm and 108 mm)

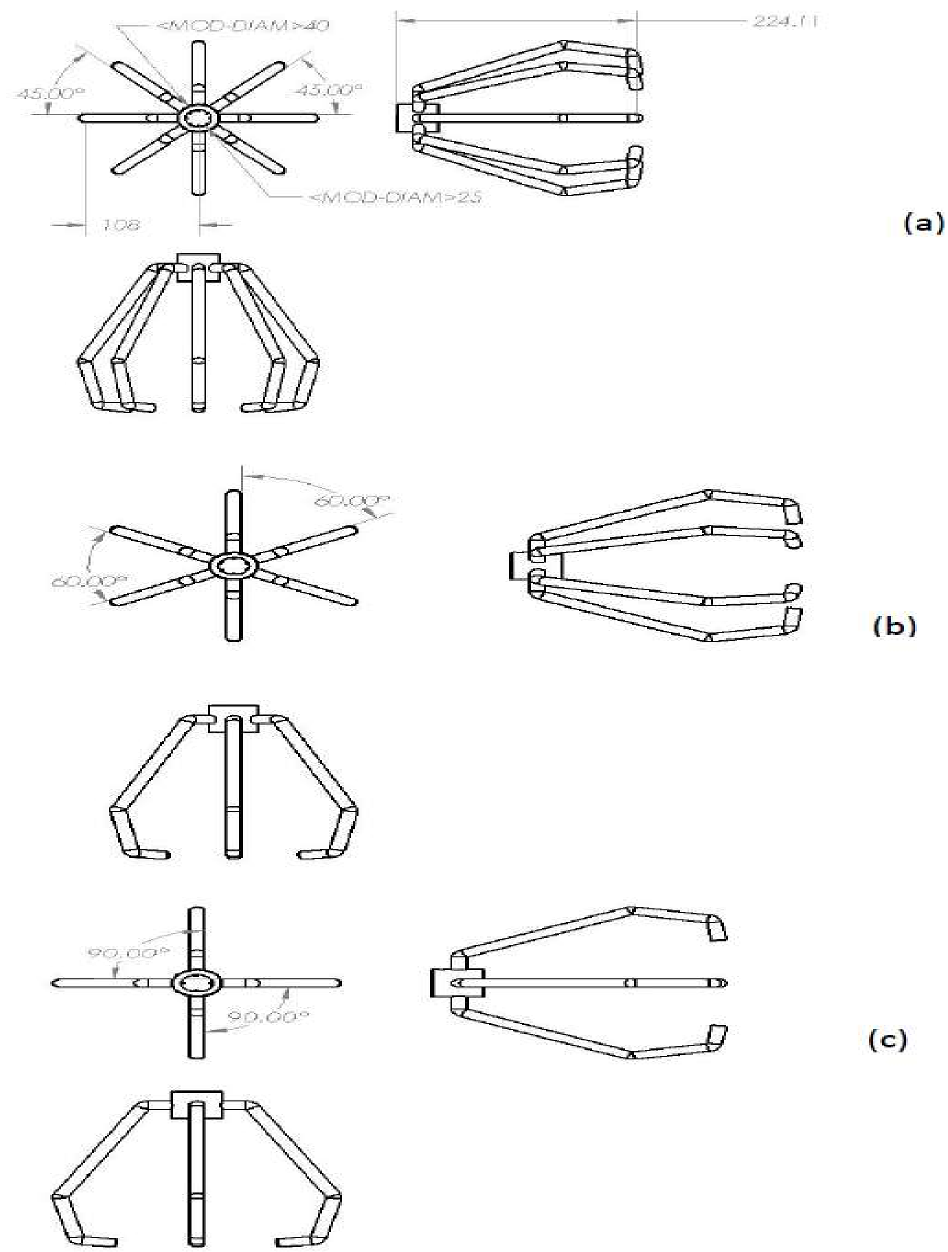

Figure 2. Agitator configuration (a) Type A-5 blades with 45° orientation (b) Type B-4 blades with 60° orientation (c) Type C-3 blades with 90° orientation

2.4 Technical parameters of the dough mixer

The technical parameters or values computed from the design analysis are summarised in Table 1.

Table 1. Technical parameters of the machine

s/n	Parameter	Angular orientation			SI Unit
		45°	**60 °**	**90 °**	
1	Volume of bowl	0.02	0.02	0.02	m^3
2	Torque on agitator	28.6	28.6	28.6	Nm
3	Circular shaft diameter	10.0	10.0	10.0	mm
5	Blade thickness	1.82	1.91	1.93	M
6	I_x on the top structure about *x* axis	2.85×10^{-4}	3.80×10^{-4}	5.71×10^{-4}	m^4
7	I_z on the top structure about *z* axis	4.48×10^{-4}	4.86×10^{-4}	4.25×10^{-4}	m^4
8	I_{ms} on the shaft about *x* and *z* axes	4.91×10^{-10}	4.91×10^{-10}	4.91×10^{-10}	m^4
9	Maximum torque developed	59.79	49.82	42.70	Nm
9	M_b required for mixing	357.6	357.6	357.6	N
10	Power requirement	3.0	3.0	3.0	Hp

2.5 Frame

The frame is made of a low carbon steel composite material to ensure even distribution of weight while still considering effective material properties, such as corrosion resistance and strength. The frame houses the electric motor and the control system. Its base also carries the bowl, with a slot created to keep the bowl rigid.

Figure 3 shows the orthographic projection and the isometric view of the dough mixer. The dimensions of all the parts of the machine have been specified in millimeters according to the parameters calculated. This is essential for independent replication of the design and production of the dough mixer.

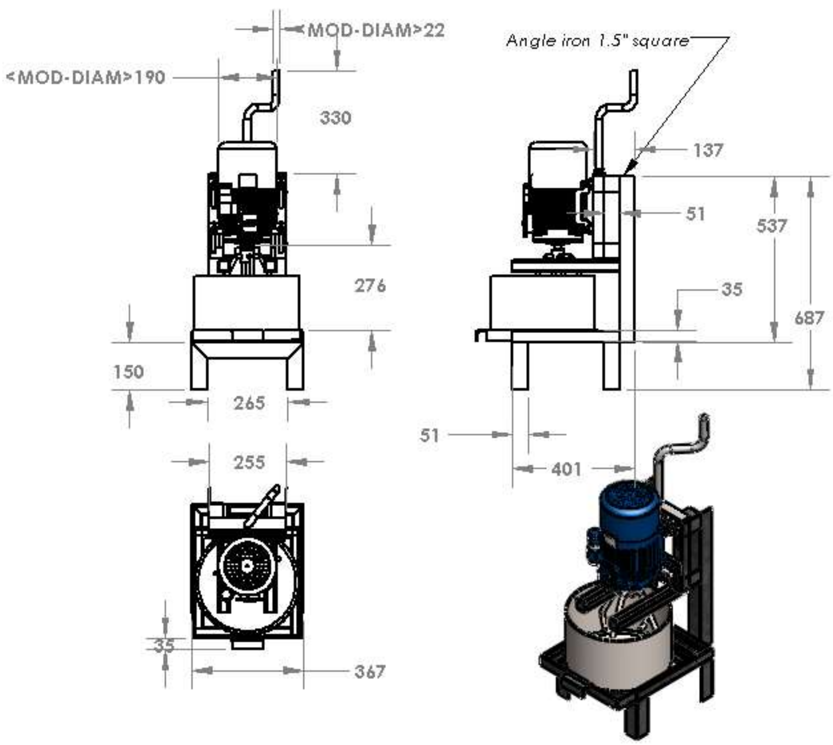

Figure 3. Orthographic projection and the isometric view of the dough mixer

2.6 Bill of engineering measurements and evaluation

The bill of engineering measurement and evaluation of the dough mixing machine is shown in Table 2.

Table 2. Bill of Engineering measurements and evaluation

S/n	Part	Qty	Unit Price (₦)	Cost (₦)
1	Bowl	1	5,560	5,560
2	Bowl Base	1	1,112	1,112
3	Electric Motor	1	27,760	27,760
4	Frame	1	2,776	2,776
5	Slider	1	1,668	1,668
6	Bolts (17)	4	888	3,552
7	Nut (17)	4	888	3,552
8	Bolt (22)	1	556	556
9	Impeller Sleeve	1	3,888	3,888
10	Agitator	18	668	12,024
11	Other bolts	4	556	2,224
12	Sheet metal		5,560	5,560
13	Welding and machining		3,332	3,332
14	Miscellaneous		5,560	5,560
	Total			₦ 79,124 ≡ $ 179.81

2.7 Performance Evaluation

Determination of effective mix proportion: A dough mixture was prepared by adding 5 kg of wheat flour, 1 kg of water, 200 g of sugar and 50 g of salt in a clean 19 *l* plastic bowl. This was then stirred using a plastic spatula and introduced into the dough mixer for homogenization, as shown in Figure 4. Performance of the different configurations of the agitators (A, B, C), speed of the shaft (250−350 rpm) and agitator geometry angle (45°− 90°) were determined in terms of the effective mix proportion of the machine, using the expression in equation (9) (Fadeyibi *et al.*, 2017). This is the degree of the effective mixing of the dough with minimal spillage obtained per time interval of the machine operation. The higher the EMP, the greater the performance of the dough mixer.

$$EMP = 1 - e^{kt} \tag{9}$$

where,

EMP = effective mix proportion (0.0− 1.0).
t = time interval of machine effective operation (5 min)
k = constant of the mixing experiment. It is related to the agitator of the mixer and can be used to predict the times required to attain 90 % homogeneous mixing (Fadeyibi *et al*., 2017).

Figure 4. Pictorial view of the dough mixer

2.8 Parameter Optimization

A response of each of the random combination of the operational variables, namely impeller type, impeller geometry and speed of the shaft, on the effective mix proportion was analysed to determine the best possible combination of the impeller configurations, for effective dough mixing, according to equation (10) (Torotwa and Ji, 2018).

$$\boldsymbol{y = f(x_1, x_2, x_3)} \qquad (10)$$

where,
y = Effective mix proportion
x_1 = number of blades (type),
x_2 = impeller geometry (deg.)
x_3 = shaft speed (rpm).

The EMP data obtained were fitted into the mathematical model in Equation (10), and the degree of fitness (R^2) was tested for linear, quadratic or cubic model possibilities. In this study, a quadratic relationship was found to fit all the parameters with a higher R^2 value compared with the other model equations tested. The resulting equation was solved subject to the conditions specified within the design criteria shown in Table 3.

Table 3. Constraints for the design criteria

		Allowable Range			
Parameters	**Unit**	**-1**	**0**	**+1**	**Constraint**
Agitator geometry angle	deg	45	60	90	$-1< \boldsymbol{\alpha \leq 1}$
Shaft speed	rpm	250	300	350	$-1< \boldsymbol{\alpha \leq 1}$
Number of blades	type	3	4	5	$-1< \boldsymbol{\alpha \leq 1}$

A slip-plot optimal design, which is a flexible design structure accommodating the quadratic model, categoric factors and their constraints was used to optimize the experimental variables. Runs are determined by a selection of criterion chosen during the build and allows the use of the three variables at three levels to determine the optimum combination of the agitator configuration found closer to the desirability index. The desirability index is an indicator of optimality of the objective function which varies from 0 to 1 (Fadeyibi *et al*., 2017). Since the goal is to maximize the shaft speed, number of blades and agitator geometry angle, the solution of the objective function will target the highest desirability index which gives the maximum value of the effective mix proportion (Thakkar *et al*., 2021; Ruiz-Hernández *et al*., 2021; Zhao *et al*., 2021).

3. Results and Discussion

3.1 Effect of blade number and agitator geometry angle on effective mix proportion

The effect of the blade number and agitator geometry angle on the effective mix proportion of the dough mixer is shown in Figure 5. The effective mix proportion decreases with an increase in the agitator geometry angle, irrespective of the speed of the mixing shaft. It is likely that great torque was develop because of the decrease in the agitator geometry angle. This might have caused the dough mixture to swirl and agglomerate together with a reduction in the clearance between the individual blades. The best agitator was the type-B with 4 blades orientation which gives higher effective mix proportion, with an increase in the geometry angle, compared with the other types of the agitator used. The type-C agitator with 3 blades orientation gave the lowest effective mix proportion compared with the other agitator types. However, at 45^o geometry angle the type-A agitator with 5 blades orientation performed better than the type-B agitator with 4 blades orientation. The reason for this distinct behavioral pattern of the mixer performance may be related to the flow pattern and energy distribution of the dough constituent materials which is experienced during the mixing operation with the agitator blades inclined at 45^o (Park *et al.*, 2014). A similar effect was reported for a static flow mixer flow by Park *et al.* (2014). Also, this agrees with Robinson and Cleary (2012), who reported an improvement in the mixing performance with the geometry, in their work on the flow and mixing performance in helical ribbon mixers.

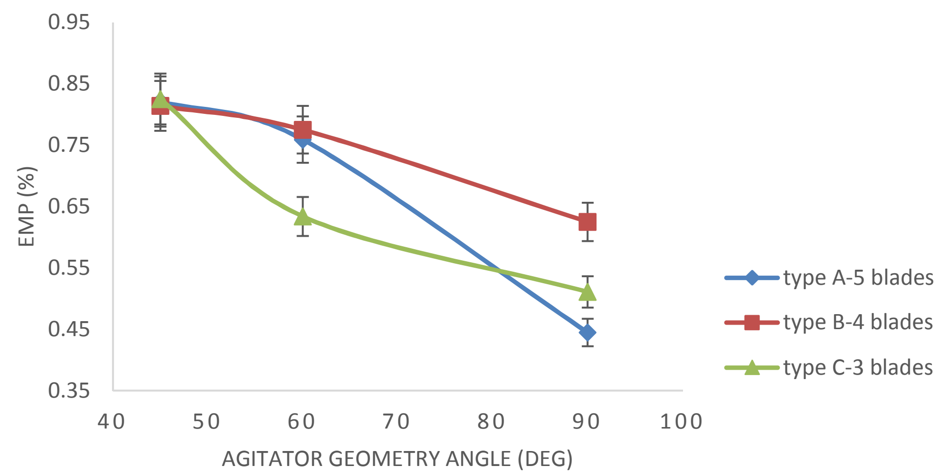

Figure 5. Effect of blade number and agitator geometry angle on effective mix proportion

3.2 Effect of agitator geometry angle and shaft speed on effective mix proportion

The effect of the agitator geometry angle and shaft speed on the effective mix proportion is shown in Figure 6. The effective mix proportion increases with an increase in the speed from 250 to 350 rpm, regardless of the agitator geometry angle. A critical behaviour of the mixer was obtained at 300 rpm, which indicates the homogeneous phase change stage in the mixing process. At this stage, the dough material is likely to change phase from unmixed to effective mixing as the mixing progresses with an increase in the speed of the mixing shaft. Thus, an effective mixing of the dough constituents was achieved just immediately after the critical speed. Irrespective of the agitator geometry angle, the homogeneity of the product began at any mixing speed greater than 300 rpm. The angular orientation of 60^o provided more effect on the overall performance of the mixer, and this may be considered as the best geometry for large scale practice. Consequently, a high speed of the mixing shaft and a 60^o agitator geometry angle may cause the development of a slip plane within the bed of the dough particles to ensure effective mixing operation. This phenomenon is likely to cause an increase in the viscosity of the materials due to decreasing cohesion between particles that may occur during slipping (Rajasekaran and Kumar, 2014; Gaikward *et al.*, 2016; Xig-hua and Zhang, 2000). This corroborates the findings of Stump and Anderssen (1997) who reported that a mixing speed of 350 rpm was sufficient to cause straining and momentum transfer from the blades to the dough during the mixing operation.

The influence of the blade number and the shaft speed on the effective mix proportion is shown in Figure 7. The mixer performance increases with an increase in the shaft speed irrespective of the blade numbers in the operation. This further explains that the product is more homogeneous at higher mixing speeds. A similar result was reported for dynamic fluids by Torotwa and Ji (2018) in their study on the mixing performance of different impeller designs in stirred vessels using computational fluid dynamics. Again, the mixer performance was higher for the agitator with 5 blades and lower for the 3 blades agitator. This supports the findings of Brabec *et al.* (2015) who reported the effect of the mixing speed on experimental baking and dough testing with a mixer. The mixer performance increases with an increase in the speed of the agitator but decreases with an increase in the blade configuration. Therefore, adequate mixing of the dough can be achieved with the combination of 350 rpm mixing speed and type A agitator with 5 blades.

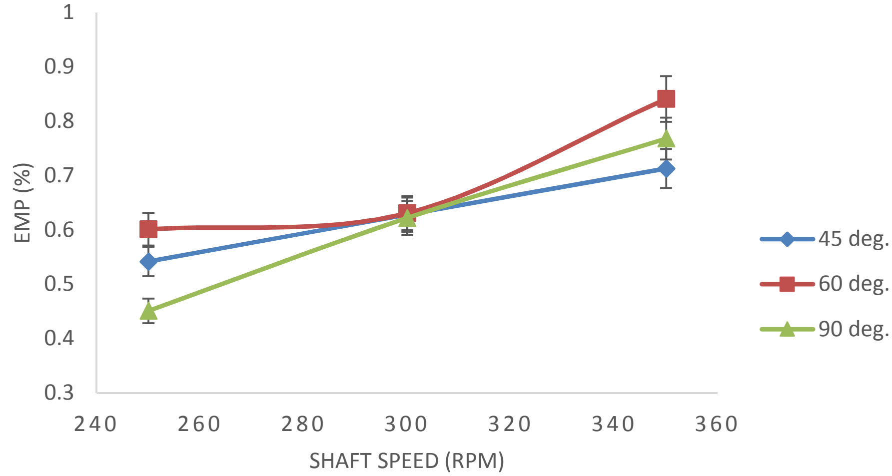

Figure 6 Effect of agitator geometry angle and speed on effective mix proportion

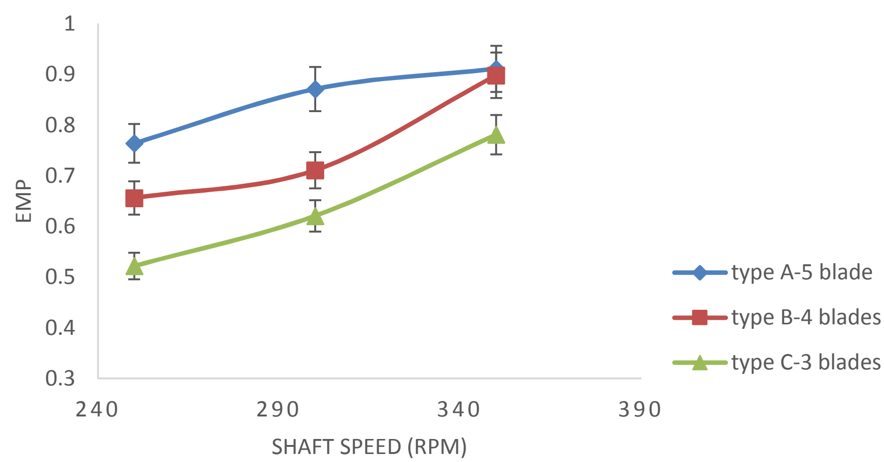

Figure 7 Effect of blade number and shaft speed on effective mix proportion

3.3 Optimal operational conditions for effective dough mixing

The results of the parameter optimization of the dough mixer for an effective mix proportion are shown in Figure 8. The desired variables occurred for type-C agitator with 3 blades, 60^{o} geometry at 250 rpm with 0.98 effective mix proportion. In a related research, Ktenioudaki *et al.* (2010) reported that the mixer parameters such as speed of the agitator and type of the mixing device affect the optimal behavior of the mixer and its product. The authors also reported that altering the mixing speed affected the rheological properties of dough. The research findings of Jongen *et al.* (2003), who studied the influence of the blade rotation speed and tip clearance on the dough deformation characteristics agrees with the optimum values obtained in the current study. Thus, this could serve as guide for engineers to acquire fundamental knowledge of the optimum parameters for an effective mixing of the dough.

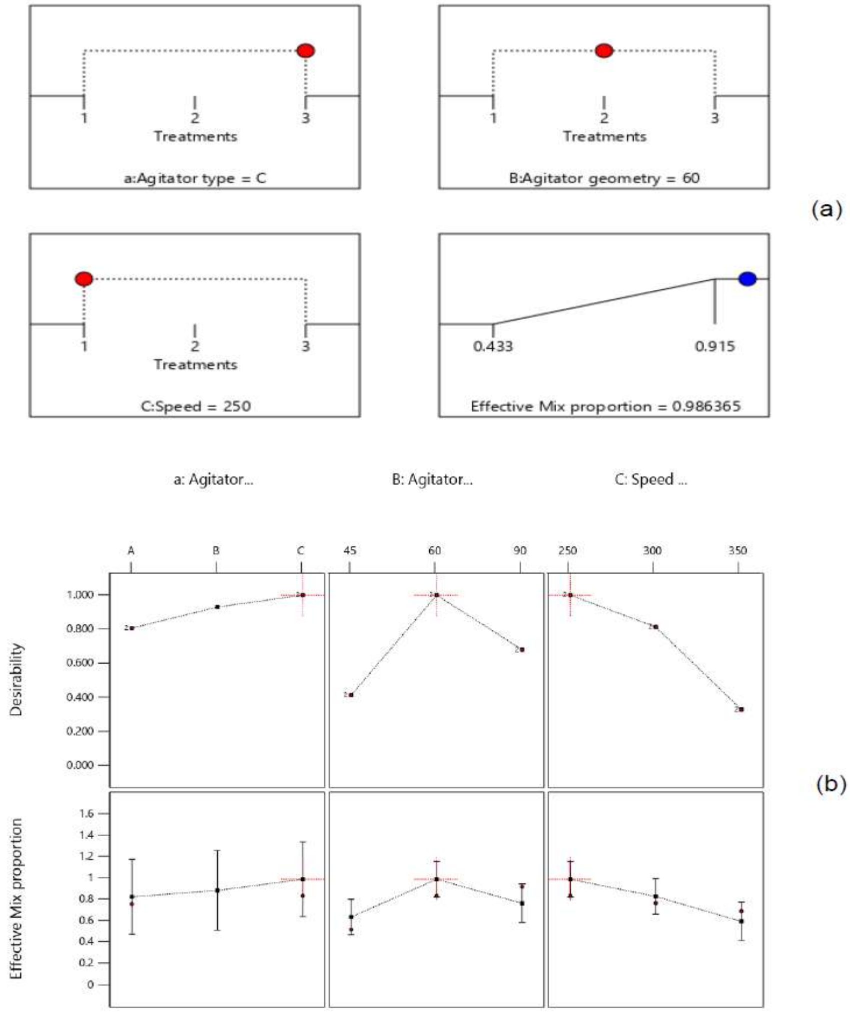

Figure 8. Optimal parameters for effective mix proportion

4. Conclusions

The following conclusions were drawn from the findings in this research.

i. A dough mixer was developed and evaluated for mixing wheat flour and other ingredients.
ii. A critical behavior of the mixer was obtained at 300 rpm, which indicates the homogeneous phase change stage in the mixing process.
iii. The angular orientation of 60^o provided more effect on the overall performance of the mixer, and this can be considered as the best geometry for large scale practice.
iv. The optimum effective mix proportion occurred for type-C agitator with 3 blades, 60^o geometry at 250 rpm with 0.98 effective mix proportion.

Acknowledgements

The authors acknowledge the technical assistance provided by the staff of engineering workshop at the National Centre for Agricultural Mechanization (NCAM), Ilorin, Kwara State, Nigeria.

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