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Development and performance evaluation of a Mix-Kneader for drying soap

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ABSTRACT

Soap is a salt of fatty acids obtained worldwide from mainly agricultural products and by-products such as plant (vegetable) oils (Yahaya et al., 2012). Drying neat soap is one of the key steps in the process of manufacturing bar soap. Currently, small and medium-scale local processors in Uganda rely entirely on tarpaulins and buckets to dry neat soap. These methods are labor intensive and take a lot of time (about 24 hours) to dry soap from 29-35% (w.b.) to the required moisture content of 15% - 21% (w.b.). Therefore, the aim of this research was to develop a Mix-kneader for drying soap in order to boost local production of bar soap. First, the different parts of the machine were designed and sized with the help of Solid Edge ST9 mechanical computer-based software. Fabrication of the component parts was done and finally, performance evaluation of the machine was carried out. At 'No' load test, the results indicated that the machine can run freely without too much noise and there were no visual breakdowns. At 'Full' load test, the Mix-kneader was able to dry 180 kg of neat soap in an average time of 15.5 minutes. The average machine capacity was approximately 560 kg/hr with a drying efficiency of 83.4%. The drying rate of the machine was calculated as 2.13 kg of water per minute. The material wastage was calculated as 1.31% which can be attributed to the fabrication errors. The developed Mix-kneader is affordable to processors and can be fabricated from any workshop within the country since it was developed from locally available materials.

Keywords: mix-kneader; drying; soap; moisture content; kneading; kneading time

INTRODUCTION

Soap remains an essential ingredient in modern living, used daily for medicinal, laundry purposes, household cleaning, and personal hygiene (Ajao et al., 2011; Chirani et al., 2021; Richardson and Collins, 2023). Soap is a salt of fatty acids obtained worldwide from mainly agricultural products and by-products such as plant (vegetable) oils (Yahaya et al., 2012). If properly harnessed, majority of plant oils and fat can be treated with strong alkaline solutions to obtain soap. Some of these materials include palm oil, coconut oil, cocoa, olive oil, and laurel oil with a strong alkaline solution (Aiwizea & Achebob, 2012; Aminadokiari Samuel, 2023; Konkol & Rasmussen, 2015). Thus, soap processing activity is a vital activity to the agricultural sector in Uganda. The process of making soap is called saponification or basic hydrolysis reaction of fat or oil. Presently, sodium hydroxide or sodium carbonate is used to neutralize the fatty acid and convert it to salt (Arasaretnam and Venujah, 2019).

Soap is manufactured in three forms which are; bar, powder, and liquid (TI, 2019; Warra, 2016). In Africa, soap making falls into three different scales namely small, medium, and industrial (large) production (Nwankwojike, 2012). The industrial production of soap involves a continuous process that requires the constant addition of fat and the removal of products. Additionally, small and medium-scale production involves the traditional batch manual and semi-mechanized processes respectively.

In Uganda and Africa in general, soap is among the most widely used consumer good besides salt and cooking oil (KPMG Africa, 2015).

Soap production in Uganda is a lucrative business that has attracted several business-minded individuals. This is due to the ready availability of raw materials (mainly palm oil) in most parts of the country. Much of the Ugandan palm oil is found in the islands of Lake Victoria (Natawidjaja et al., 2015). Over 20,000 hectares in these areas are under the plantation of palm oil trees by Business and Industrial Development Corporations (BIDCO) and an increasing number of wealthier out-growers (Bigirwa, 2018; Ssemmanda and Opige, 2018).

Bar soap is the most popular form of soap in Uganda (Nakaweesi, 2018). It is a low-cost cleaning detergent that is found in most homes (UNBS, 2011). Mukwano Industries and BIDCO Uganda are the main producers of laundry bar soap supplying over 37 million consumers on a daily basis (UBOS, 2016). This is because the majority of the local investors are small and medium-scale processors, employing mostly manual and semi-mechanized production methods. For instance, the mixing of ingredients is done manually with a wooden ladle, and the drying of neat soap is done by pouring the material on tarpaulins in still air. It takes about 24 hours to dry soap from 29-35% (w.b.) to the required moisture content of 12-15 % (w.b.) for toilet soap and 15% - 21% for laundry soap (Luis, 2016; Warra et al., 2011). This greatly slows down the entire production process making it difficult for processors to consistently meet their customers' demands. These methods also involve strenuous human efforts and time input making it unattractive and less productive for small and medium-scale processors.

Soap drying machines have been developed and are commercially available on the international market (Anon, 2018). However, these machines are not easily accessible to small and medium-scale processors due to high purchase prices. Therefore, there was a need to develop a machine for drying soap using locally available materials.

In concern to this, a Mix-kneader machine was developed to boost the daily production capacity of small and medium-scale processors. The machine is expected to have a strong impact on the soap industry as it tackles the issues encountered by the small and medium-scale processors in Uganda. It also addresses the reduction of the workforce, production hours, and energy consumption as well as the cost associated with the overall soap-making process.

MATERIALS AND METHODS

Description, principle, and mode of operation of the Mix-kneader

The Mix-kneader (Figure 1) essentially consists of four mechanisms namely; the power transmission, kneading, cooling, and discharge mechanisms. The power transmission mechanism consists of an electric motor as a prime mover, a reduction gearbox, Pinion, and a Gear drive for transmitting motion from the gearbox to the sigma blade shafts. The kneading mechanism consists of basically counter-rotating sigma blades (2) mounted on horizontal axis shafts in a W-shaped trough and the discharge mechanism consists of the exit cute located below the trough.

The machine uses the shearing and kneading mechanism to dry neat soap during which the sigma blades create high shear and kneading action. The blades rotate towards each other at different speeds to produce shearing forces between the two blades and between them and the trough walls. Each blade moves the material in opposite directions providing excellent cross-kneading of all raw materials. The kneading action is a combination of bulk movement, stretching, folding, dividing, and recombining as the material is pulled and squeezed against the blades and side walls. This action is accelerated by the water jacket for circulating cold water around the side walls of the kneading trough. In this case, heat is transferred by convection from the hot neat soap at a temperature between (60 0C – 70 0C) to the inside trough surfaces. This heat is then transferred by conduction through the steel walls and finally, the heat is transferred by convection from the outside walls of the trough to the cooling water at 20 ^{0}C.

During operation, neat soap material is loaded into a running machine through the top of the trough to approximately three-quarters (¾) of its total volumetric capacity. The tip speed of the Mix-kneader is limited to 45 rpm. During kneading cold water is poured into the water jacket to facilitate rapid cooling of neat soap. Since the cooling process is not continuous, hot water is frequently taken out as more cold water is added in order to achieve high heat transfer from the neat soap, hence achieving faster drying. After the soap has achieved the required moisture content (15% - 21% w.b), the exit cute is opened while the machine is still running for the sigma blades to discharge the dried soap. The discharge of the material from the trough is achieved through the bottom exit cute.

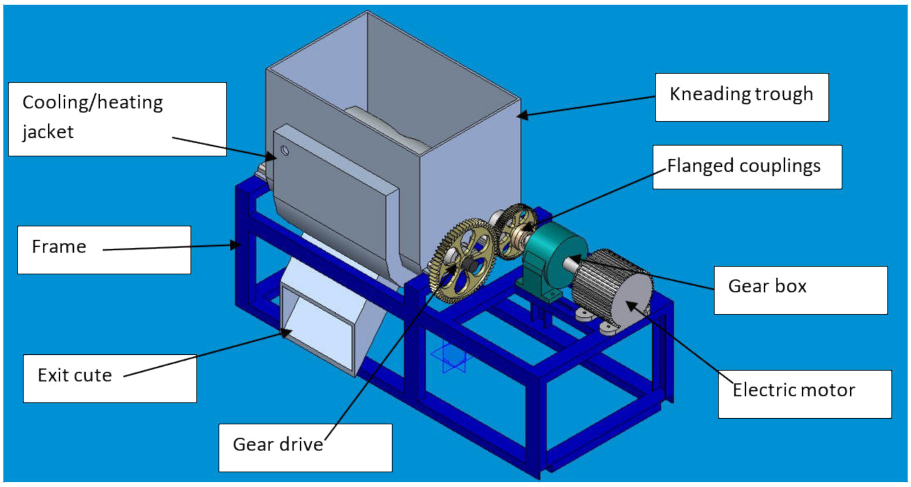

FIGURE 1: Isometric view of the Mix-kneader.

Design of component parts

Design considerations

During the design phase, careful consideration was given to; the power required for kneading, physical properties of soap (like viscosity and density), required output per hour per day (machine capacity), kneading time, and desired moisture content of soap after kneading. Other considerations were the cost of construction, labor requirement for machine operation, and the ease of replacement of component parts in case of damage or failure.

Design of the kneading trough

The kneading trough is a W-shaped trough having an upper rectangular section and the bottom half-cylindrical section as shown in Fig. 2. The volume (VT) of the trough was calculated from Equation 1 where ρ (kg/m3) is the bulk density of neat soap and Q (kg/hr) is the target production capacity required by the medium-scale processor. The design machine production capacity was 5 metric tonnes/day as required by the target processor. This is approximately 625 kg/hr considering eight working hours per day. The kneading time of 20 minutes was considered (Connelly and Kokini, 2006). An average bulk density of neat soap of 975 kg/m3 was considered as suggested by Luis (2016).

$$V_T = \frac{Q}{\rho} \quad (1)$$

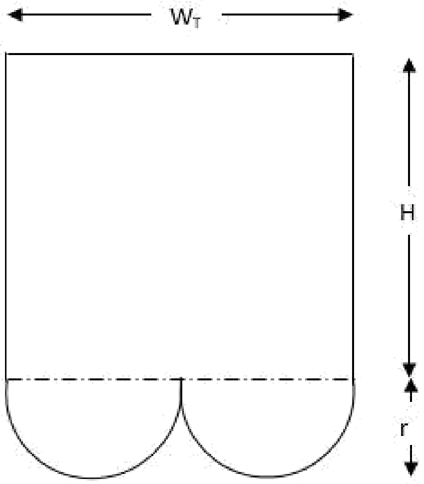

FIGURE 1: Side view of a kneading trough.

Design of the sigma blades

Two blades of sigma shape were designed. As seen in Figure 3, the sigma blades are slightly curved to overcome the forces acting against them and also to allow for effective mixing and kneading of neat soap. The sigma shape enables a steady flow of neat soap from the sidewalls of the kneading trough to the middle of the trough. Major design parameters for the blades included length, width, inside and outer curvature, tilt angle, and thickness.

The blade width, Wb, and length, Lb were determined from the dimensions of the kneading trough. Equation 2 was used to calculate the blade width considering a clearance, c of 2 mm. Other parameters of the blade like the curvature, tilt angle (β), neck width (wth), and rounds were determined graphically using geometrical tools.

$$W_b = \frac{W_T}{2} - c \quad (2)$$

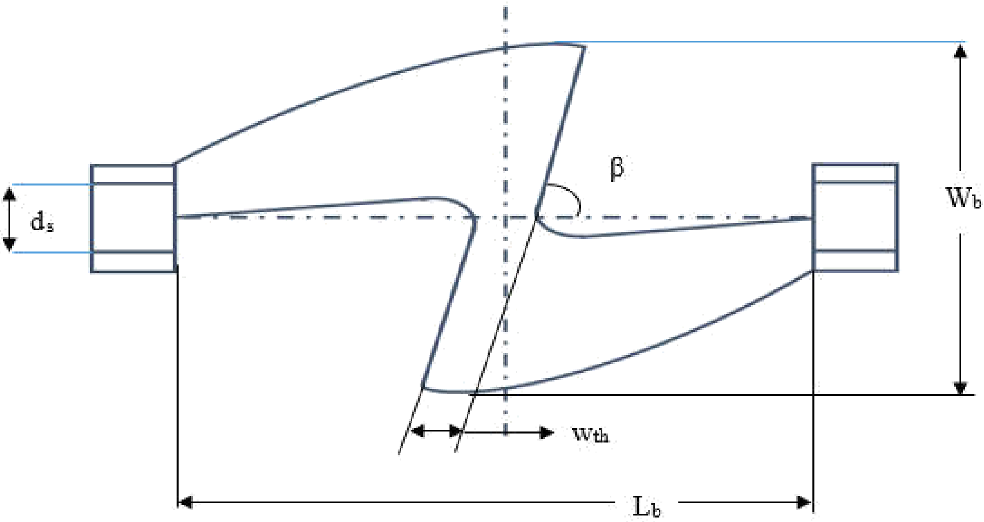

FIGURE 2: Sigma blade parameters.

Design of the transmission gear drive system

In the design of a gear drive, the following were considered as discussed by Shiva (2022); 1) the power to be transmitted, 2) the speed of the driving gear (pinion) and the driven gear (big gear), 3) diameter and number of teeth of the pinion and gear, 4) mass and weight of the pinion and gear, and 5) the center distance.

***Determination of the center distance*, C**

The center distance was determined from the width, W_T of the kneading trough as shown in Equation 3.

$$c = \frac{W_T}{2} \quad (3)$$

Determination of the diameter of the Pinion and Gear

The diameters of the pinion (driver gear) and the driven gear were calculated from the velocity ratio Equation 4. This was done by considering a velocity ratio of 3:2 and a maximum tip speed of 45 rpm as recommended by Connelly & Kokini (2006) and Dickey & Fasano (2004).

$$\frac{\omega_G}{\omega_p} = \frac{D_P}{D_G} = \frac{N_P}{N_G} \ldots \ldots \ldots (4)$$

Where;

W_G is the speed of the gear, D_G the pitch circle diameter of the gear, and T_G is the number of teeth of the gear. W_P, D_P, and T_P is the speed, pitch circle diameter, and the number of teeth of the pinion.

Determination of the number of teeth of the gear and pinion

The number of teeth for the pinion and gear was calculated from the relationship between diametral pitch (P), Number of teeth (N), and pitch diameter (D) as shown by Equation 5. A standard diametral pitch of 2 was considered (Feng *et al.*, 2019; Khurmi and Gupta, 2005).

$$P = \frac{N}{D} \ldots \ldots \ldots (5)$$

Standard proportions of gear systems as discussed by Khurmi & Gupta (2005) were used to specify other design parameters for the gear and pinion, considering a pressure angle of 20^0 and a full-depth involute system.

Calculation of mass and weight of the gear

The mass of the gear, m_G was analytically calculated using Equation 6.

$$m_G = br\pi\rho \ldots \ldots \ldots (6)$$

Where b is the face width of the gear, r is the radius of the gear, ρ and is the density of the material from which the gear was made (Aluminium material). Also, the standard face width of 65 *mm* corresponding to a diametral pitch of 2 was used.

Power required for kneading

The power required for mixing and kneading operation was determined according to; 1) the amount and viscosity of neat soap in the kneading trough and 2) the position, type, speed, and size of the sigma blades using Equation 7.

$$P = P_o \times \rho_s N^3 D_b^5 \ldots \ldots \ldots (7)$$

Where P_o is the power number which is a function of Reynolds number (Re) and Froude number (Fr), ρ_s is the density of neat soap in kg/m³, D_b is the diameter of the blade and N is the speed of the blade in rps.

$$P_o = K(Re)^n(Fr)^m \ldots \ldots \ldots (8)$$

Where K, n, and m are factors related to the geometry of the agitator, which is found by experiment (Fellows, 2004). Reynolds Number is given by Equation 9.

$$Re = \frac{\rho_s N D_b^2}{\mu_s} \ldots \ldots \ldots (9)$$

Where μ_s is the viscosity of soap in Pa. An average viscosity of 400 cp was used as provided by Luis (2016). Froude Number is given by Equation 10.

$$Fr = \frac{D_b N^2}{g} \ldots \ldots \ldots (10)$$

Where g is the acceleration due to gravity.

Selection of the reduction gearbox

The purpose of the reduction gearbox is to reduce the speed (rpm) of the electric motor. A reduction gearbox with a speed reduction ratio of 30:1 was procured to reduce the speed of the electric motor to the required operating speed.

Design of the shaft

The shaft was designed based on two factors; (1) Strength basis and (2) Rigidity. The strength factor was based on permissible stresses whereas the rigidity was based on the deformation caused in the shaft. In the design of the shaft, its length and diameter, the weight of the components it carries, the forces, torque, and bending moments acting on it, and the total deflection caused by the forces were considered.

Calculation of the tangential (F_t) and normal (F_N) forces acting on the pinion

The forces acting on the shaft are; 1) the weight of the blade, 2) the resultant force (reaction) acting at the support bearing, 3) the weight of the gear and the centrifugal force (tangential and radial/normal components) generated due to rotation of the pinion and 4) the reaction at the coupling (both vertical and horizontal components). The tangential force was calculated using Equation 11, where T is the torque on the pinion and r_p is the radius of the pinion.

$$F_t = \frac{T}{r_p} \ldots \ldots \ldots (11)$$

The torque on the pinion is the ratio of power transmitted through the shaft to the rotational speed (rps) of the pinion as given by Equation 12.

$$T = \frac{P \times 60}{2\pi \times N_P} \ldots \ldots \ldots (12)$$

The normal/radial component was calculated using Equation 13 where φ is the pressure angle of the pinion (equal to 20^o).

$$F_N = F_t . tan\varphi \ldots \ldots \ldots (13)$$

Determination of the resultant force acting on the shaft

To determine the resultant force, the loading on the shaft was resolved into both horizontal and vertical planes. The horizontal and vertical bending moment and shear force diagrams were then constructed and the resultant maximum bending moment, M_{max} calculated using Equation 14.

$$M_{max} = \sqrt{(M_V^2 + M_H^2)} \ldots \ldots \ldots (14)$$

Determination of the shaft diameter

The determination of the shaft diameter was based on the *Maximum Shear Stress Theory* (*MSST*) since it is subjected to the combined effect of both bending and twisting/torsional moments. The *equivalent twisting moment* Equation 15 and the permissible design shear stress Equation 16 were used in this case (Saradava *et al.*, 2016; Sule *et al.*, 2018; TI, 2019).

$$\tau_{max} = \frac{16}{\pi d^3}\sqrt{(K_m M)^2 + (K_t T)^2} \ldots \ldots \ldots (15)$$

$$\tau_{per} = \frac{S_{yt}}{2F.O.S} \ldots \ldots \ldots (16)$$

Where τ_{max} is the maximum shear stress on the shaft, d is the shaft diameter, τ_{per} is the permissible shear stress for the shaft material, S_{yt} is the yield strength under tension, *F.O.S* is the factor of safety, K_m and K_t are the combined shock and fatigue factors for bending and torsional moments respectively. The allowable/permissible shear stress was calculated considering a factor of safety of 2 as recommended by (Pedersen, 2018). To account for shock and fatigue in rotating shaft with gradually applied loads operating condition, K_m = 1.5 and K_t = 1 (suggested by *ASME* shaft design code (Babu, 2009; Bhandari, 2010; Ejiko *et al*., 2018; Saradava *et al*., 2016).

Calculation of the maximum deflection caused in the shaft

The bending moment Equation 17 was obtained using Macaulay's method (Egelhoff and Odom, 2014; Fadare and Akanbi, 2010; Stephen, 2007). The double integration technique as discussed by Fadare & Akanbi (2010) was applied to obtain the general deflection Equation 18.

$$\frac{d^2y}{dx^2} = \frac{1}{EI}(979.58x - 166.67) \quad (17)$$

$$\therefore y = \frac{1}{EI}\left[\frac{979.58x^3}{6} - \frac{166.67x^2}{2}\right] \quad (18)$$

Where '*E*' is the Modulus of Elasticity of the material of the shaft (stainless steel 304) and is equal to 195.199 *GPa*, '*I*' is the moment of inertial, and '*x*' is the distance at any point along the shaft from point A. The moment of inertial was calculated considering a circular cross-section for the shaft.

Design of the water jacket

Generally, in the design of the water jacket, it was desirable to calculate the area of heat exchange required to perform the cooling operation and the outlet temperature of hot water. It was also desired to cool neat soap from the temperature range of 60 ^{0}C – 70 ^{0}C to around room temperature (25 ^{0}C– 28 ^{0}C).

The cooling process involves hot neat soap at temperature *T* (60 ^{0}C – 70 ^{0}C) which transfers heat to circulating cold water at temperature *t* (20 ^{0}C), through a steel surface of thickness of 3 mm. Heat transfer is carried out from the hot neat soap to the cooling water. Initially, heat is transferred by convection from the hot neat soap at temperature *T* to the inside trough surfaces at temperature T_W. This heat is then transferred by conduction through the steel walls, so there is a temperature drop from T_W to t_W (temperature of the outside wall of the trough). Then heat is transferred by convection from the outside walls of the trough to the cooling water at temperature t. The area of the trough inside surface in contact with the hot neat soap is called A_H, while that in contact with the cold water is A_C. Since the trough surfaces are flat, these areas coincide, and therefore $A_H = A_C$.

Three assumptions were made during the design of the water jacket 1) heat losses to the surroundings are negligible 2) no airbags are formed inside the water jacket and 3) the universal heat-transfer coefficient is constant.

The overall heat transfer area and the associated temperatures were calculated through simultaneous solving of Equations 19, 20, 21, 22, and 23.

Heat convection on the side of hot neat soap

$$Q = h_h(T - T_W)A_h = \frac{T - T_W}{1/(h_h A_h)} \quad (19)$$

Where h_h is the convective heat-transfer coefficient of neat soap.

Heat conduction through the trough surface

$$Q = \frac{k}{e}(T_W - t_W) = \frac{T_W - t_W}{e/(kA_{ml})} \quad (20)$$

where k is the thermal conductivity of the steel, e is the thickness of the sheet plate used for making the trough, and A_{ml} is the logarithmic mean area, defined by

$$A_{ml} = \frac{A_c - A_h}{ln\left(\frac{A_c}{A_h}\right)} \quad (21)$$

Heat convection on the side of the cold water in the water jacket.

$$Q = h_c(t_W - t)A_c = \frac{t_W - t}{1/(h_h A_h)} \quad (22)$$

In which h_c is the individual convective heat-transfer coefficient of the cold water.

The universal heat transfer coefficient U_C, was calculated by

$$\frac{1}{U_c} = \frac{1}{h_h(A_h/A_c)} + \frac{e}{k(A_{ml}/A_c)} + \frac{1}{h_c} \quad (23)$$

Design of the frame

The frame is a structure that supports all the machine components i.e., the Kneading trough, electric motor and gear box, the gear drive arrangement and the sigma blades. Hence, it must be strong enough to carry the weight of all these components and as well as withstand the vibration that may arise from the operation of the machine. Also, the machine must be comfortable in operation for the human operator. Design for average was adopted to determine the dimensions of the frame as well as the location of the various component of the machine with respect to the frame. This was to ensure the comfort of the operators.

Material selection

During material selection, materials which are cheap, corrosion resistant, chemically stable with soap and locally available were selected. Mild steel (*MS*) was used for the fabrication of the kneading trough, frame, shafts, and all other protective guards for the exposed machine components because of its good physical properties such as strength and hardness. Mild steel also has good workability properties such as easy fabrication. The electric motor was purchased according to the power requirement of the machine. Gears, gearbox, and pillow block bearings were also purchased in accordance with the design specifications. Standard items (nuts, bolts, washers, etc.) were purchased to march the design specifications.

Fabrication of major components and assembling

The prototype of the Mix-kneader was fabricated based on dimensions obtained from the design calculations. Fabrication of the machine parts was done at Waysai Agricultural Machinery Workshop in Kawempe, Kampala. The general fabrication steps were followed that is; measuring and marking out, cutting out, welding, boring, filler process, assembling, and then surface finishing.

Unlike other machine components, the two sigma blades were manufactured through the process of sand casting following the procedure recommended by Murguia *et al*. (2016).

The basic steps for casting process were followed that is; pattern making, core making, molding, melting and pouring and surface finishing. The kneading trough was fabricated from MS sheet metal plate of 3 mm thickness. The support frame was fabricated using a 75 mm U – section bar. The fixed type end connection was used in holding the frame members together as members were to be eventually welded together to give adequate rigidity.

The frame was adequately loaded at appropriate locations according to the weights of the various components of the machine it is intended to carry at these locations. And finally, all the protective guards and covers were fabricated from Mild Steel plates of 1.5 mm thickness. The guards were fabricated to protect delicate and moving components such as the gear drive system, gearbox, electric motor, and bearings.

Performance evaluation of the developed Mix-kneader

This was an important step in the development of the Mix-kneader as it helped in determining the efficiency and optimal operating conditions of the developed Mix-kneader. The evaluation was carried out at Tamam Home Care Limited, a medium-scale bar soap processing facility in Wakiso district. First, the machine was test run for 30 minutes without loading. This was done to study the unloading behavior of the machine. The machine was then tested when loaded to determine its optimum operating conditions as well as its efficiency.

Optimum feed capacity

To determine the optimum machine feed capacity, the machine was loaded with 60 kg of neat soap (which is almost ¼ of the total machine volume) of 32% (w.b) moisture content at a fixed blade speed of 45 rpm and 30 rpm for the high and low-speed blades respectively. The time taken for the soap material to reach a moisture content of about 15% (w.b) was recorded. The experiment was repeated four times by using 100 kg, 120 kg, 150 kg, and 180 kg batches.

Optimum kneading time

The optimum feed capacity was used to determine the optimum time required for the machine to dry soap to the appropriate moisture content. Nine recordings were made using 180 kg batches of neat soap of varying moisture content while varying the kneading time from 12 – 20 minutes.

Uniformity of dried soap in the different regions of the kneading trough

To determine the uniformity of the dry soap produced by the Mix-kneader, the kneading trough was divided into six regions. A, B, and C correspond to the left, middle, and right part of the half cylindrical section of the kneading trough where the high-speed blade (45 rpm) rotates from. D, E, and F correspond to the left, middle, and right part of the half cylindrical section of the kneading trough where the slow-moving blade (30 rpm) rotates from. Using the optimum operating mass of 180 kg and average kneading time of 15.5 minutes, the moisture content of the dry soap from all six sections of the machine was recorded using the moisture meter before discharging it. The experiment was repeated four times using the same operating conditions in order to determine the uniformity of dry soap in the kneading trough.

Mix-kneader efficiency parameters

The efficiency of the machine was determined in terms of its machine capacity, drying efficiency, discharge efficiency, and drying rate using Equations 24, 25, 26, and 27 respectively. Neat soap samples of 180 *kg* at different initial moisture content ranging from 29% - 35% (w.b) were used to determine the machine efficiency.
For each trial, the machine was run for 15.5 minutes which is the optimum kneading time, and the discharged (output) soap from the machine, the undischarged soap, and the final average moisture content of dry soap were recorded.

$$\text{Machine capacity} = \frac{Q_0}{t} \times 60 \left(\frac{\text{kg}}{\text{hr}}\right) \quad (24)$$

$$\text{Drying efficiency}, \eta = \frac{T_1 - T_2}{T_1 - T_W} \quad (25)$$

$$\text{Drying rate}, = \frac{m_x}{t} \quad (26)$$

Where m_x is the mass of water/moisture removed.

$$\text{Discharge efficiency} = \frac{Q_0}{Q_0 + Q_r} \times 100(\%) \quad (27)$$

RESULTS

Design calculation results of Mix-kneader components

The results for calculated design parameters are summarized in Table 1. Figure 4 shows the bending moment and shear force diagrams of the shaft loading condition for both the horizontal and vertical plane.

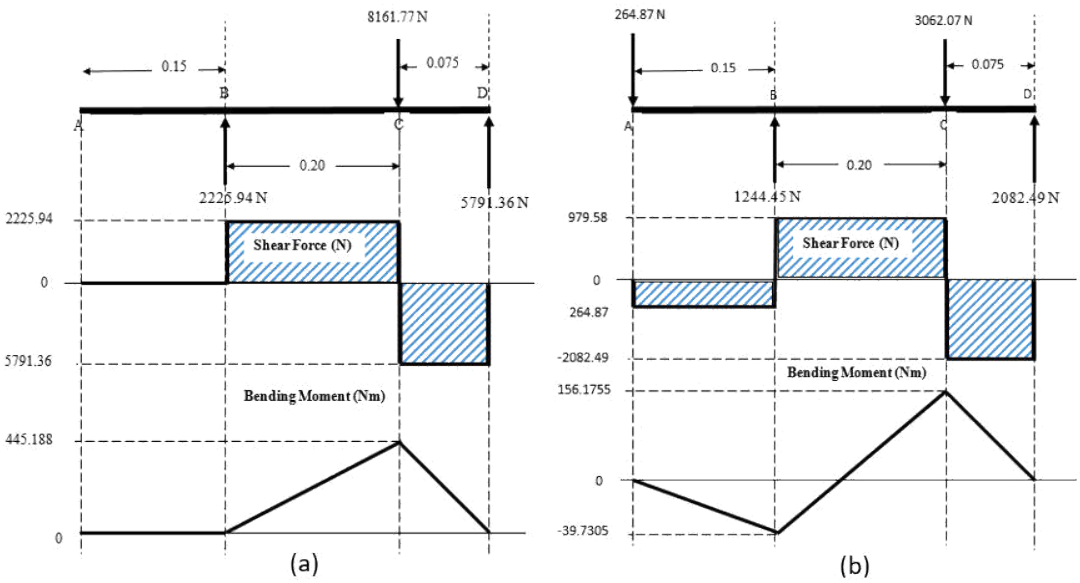

FIGURE 4: Shear force and bending moment diagrams, (a) horizontal plane and (b) vertical plane.

TABLE 1: Results for calculated design parameters.

No.	Parameter	Value	Units
	Kneading trough design		
1	Machine Capacity	625	Kg/h
2	Volume	300	Litres
3	Width	650	mm
4	Length	760	mm
5	Height	500	mm
6	Mass	50.7	kg
	Sigma blades design		
7	Length	760	mm
8	Width	321	mm
9	Mass	27	kg
10	Clearance	2	mm
	Pinion and Gear Design		
11	Gear diameter	390	mm
12	Pinion diameter	260	mm
13	Center distance	325	mm
14	Gear speed	30	rpm
15	Pinion sped	45	rpm
16	Mass of the gear	21	kg
17	Mass of the pinion	9.32	kg
18	No. teeth of the pinion	21	
19	No. teeth of the gear	31	
20	Face width	65	mm
	Shaft design		
21	Motor capacity	4	kW
22	Shaft diameter	50	mm
23	Length of the shaft	425	mm
24	Tangential force	8161.77	N
25	Normal force	2970.64	N
26	Torque	1061.03	Nm
27	Maximum Bending Moment	471.7872	Nm
28	Permissible shear stress	51.75	MPa
29	Maximum deflection caused	0.00005328	mm
	Frame design		
30	Height	600	mm
31	Length	1200	mm
32	Width	700	mm

Fabrication and assembling of the Mix-kneader

Error! Reference source not found. (a) shows the final assembled prototype of the Mix-kneader developed. The volume of the kneading trough was 300 L. A rectangular opening of 200 mm x 100 mm was provided at the bottom of the trough. This opening connects to the discharge/exit cute. The water jacket of volume 40 L was attached to the walls of the kneading trough through permanent weld joints. A water inlet of diameter 32 mm and outlet of diameter 40 mm were attached.

Protective guards were fabricated from 1.5 mm thick sheet plates to cover all the delicate machine parts like the electric motor, bearings, gears, and the gearbox reducer. **Error! Reference source not found.** (b) shows a pair of surface finished sigma blades which were casted from Aluminium metal. The mass of each sigma blade was measured as 28.3 kg, making a total mass of 56.6 kg. The mass of the gearbox and the electric motor was 68 kg and 43 kg respectively and the overall weight of the Mix-kneader with all components assembled was 234 kg. Rubber rollers of diameter 8” were finally bolted on the frame for easy moving of the machine.

(a) (b)

FIGURE 5: (a) Final fabricated prototype of the Mix-kneader fully assembled (b) Surface finished sigma blades.

Performance evaluation results

Test at 'No' load

Performance evaluation results of the developed Mix-kneader at 'No' load test showed that, the it can run freely without too much noise and there were no visual breakdowns.

Optimum machine feed capacity

Figure 6 shows the average time for the machine to adequately knead each quantity of neat soap. It can be seen that the more the machine is loaded, the longer it takes to dry neat soap. To avoid neat soap from splashing off from the kneading trough, it was found out that the Mix-kneader should not be loaded with more than three-quarters of the trough's total volume. Therefore, for smooth running and maximization of the Mix-kneader, it should be loaded with about 150 kg – 180 kg of neat soap.

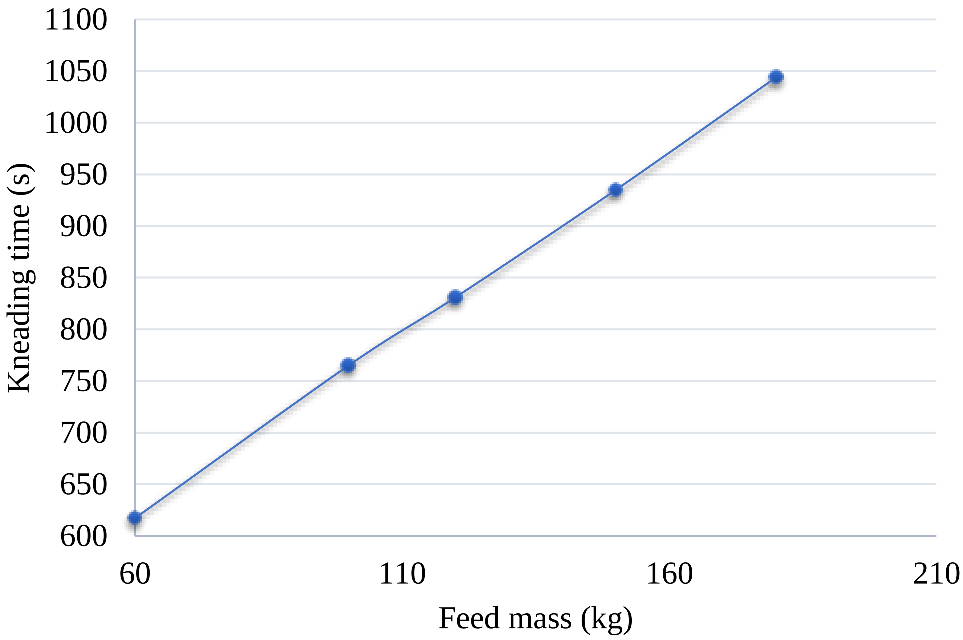

FIGURE 3: A graph of feed capacity (mass, kg of neat soap) vs kneading time of soap.

Optimum kneading time for drying soap

The initial moisture content prior to kneading was 32% *w.b* for the sample used. **Error! Reference source not found.** shows the percent average moisture content of dry soap obtained at different times of kneading from 12 – 20 minutes using a feed mass of 180 kg. Generally, it can be seen that the moisture content of neat soap gradually decreased with respect to time. This means that, as kneading proceeds, the machine is able to extract water from neat soap and hence soap is able to dry.

Optimum (desired) moisture content of 15% *w.b* was achieved after 15 minutes of kneading. Prolongation of the kneading time up to 17 minutes continued to extract moisture from soap up to about 13% at a nearly constant drying rate. However, after 20 minutes of kneading, the moisture content of soap remained almost constant at 11% level. At this level, it was no longer necessary to continue the kneading process since the machine was unable to extract any more moisture. Therefore, the optimum kneading time was between 15-16 minutes as shown by the graph in **Error! Reference source not found.**.

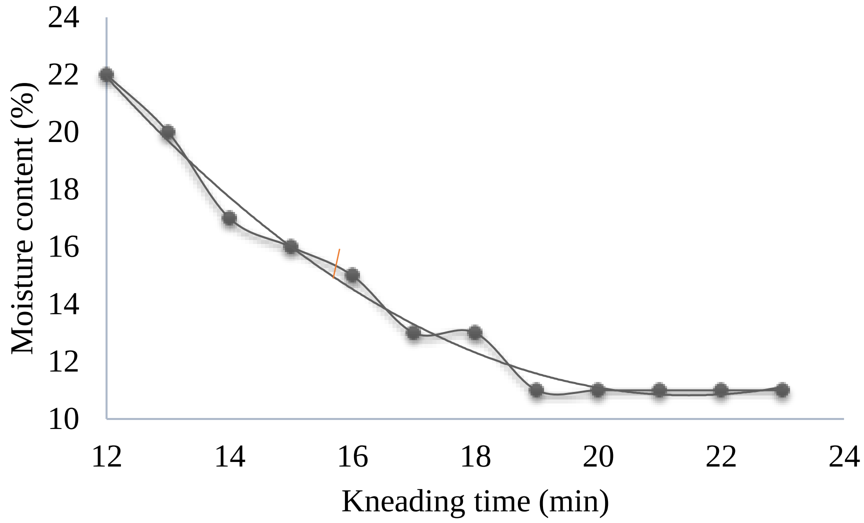

FIGURE 7: A graph of moisture content (%) vs kneading/drying time (min).

Uniformity of MC of the dried soap in different regions of the kneading trough at 15.5 minutes of kneading

From FIGURE 4 and TABLE 2, it can be seen that for each trial, the moisture content of dry soap in region B and E is low compared to other region as defined in sub-section 2.5.3 of this manuscript. It can also be seen that the moisture content of dried soap varies across each region for each trial experiment made.

Descriptive statistics of moisture content data series by regions of the kneading trough are summarized in TABLE 3. The mean moisture content of the dried soap varies between 15.5% and 18.5% with the lowest and highest experienced in regions B and C respectively. The co-efficient of variation varies between 3.17% and 8.33%. Moisture content values across all regions have standard deviation varying from ±0.8% to ±1.7%.

TABLE 2: Test results for determining the uniformity of dry soap in different regions of the kneading trough.

Trial No.	Mass (kg)	Moisture content (%) in different regions of the trough						Average moisture content (%)
		A	B	C	D	E	F	
1	180	17	15	19	19	16	18	17.2±1.6
2	180	15	14	18	16	15	18	15.8±1.7
3	180	17	16	18	17	16	17	16.5±0.8
4	180	18	17	19	18	16	19	17.8±1.2

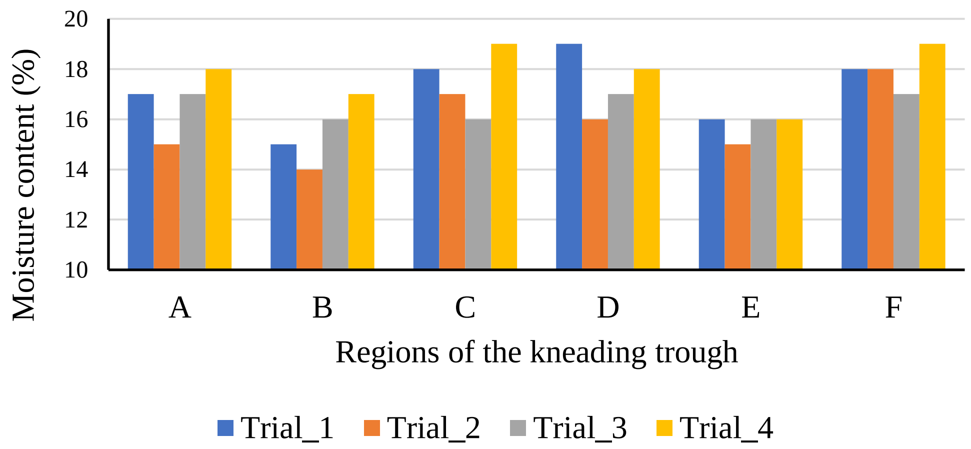

FIGURE 4: A bar graph showing moisture content of dried soap inside the different regions of the kneading trough.

TABLE 3: Summary of descriptive statistics of moisture content of dried soap in different regions of the kneading trough.

Region	Mean	Min	Max	StDev	CV
A	16.75	15	18	1.258	7.51
B	15.50	14	17	1.291	8.33
C	18.5	16	19	0.577	3.12
D	17.5	16	19	1.291	7.38
E	15.75	15	16	0.5	3.17
F	18	17	19	0.816	4.54

StDev: Standard Deviation; CV: Coefficient of Variation.

Mix-kneader efficiency parameters at 15.5 minutes of kneading

The Mix-kneader efficiency parameters were calculated based on the results in Table 4. The mix-kneader has an average machine capacity of approximately 560 kg/hr (calculated using Equation 24) and is able to operate continuously for eight hours each day. The Mix-kneader was able to dry soap in the with a drying efficiency of 83.4% according to Equation 25. When loaded at full capacity (180 kg), the machine was able to extract 32.97 kg of water from neat soap in an average time of 15.5 minutes. This means that neat soap is able to dry at a nearly constant rate of 2.13 kg of water per minute using the developed mix-kneader.

During this kneading period, the soap was able to cool from an average temperature of 64.9 OC to 33.3 OC. The amount of water used to cool each 180 kg batch of neat soap was 100 L. since the cooling process is a batch system, the water in the jacket was changed at the rate of 20 L every after three minutes. The ease and efficiency of exiting/discharging the dry soap from the machine was also tested. The machine has a discharge efficiency of 77.1%, which was calculated from Equation 27. The undischarged dry soap was also recovered easily by hand without any injuries. The material wastage by the developed Mix-kneader was calculated as 1.31%.

TABLE 4: Set up table for determining the Mix-kneader efficiency parameters.

Trial No	Mass of Neat Soap, Q_f (kg)	Output mass Q_o (kg)	Undischarged soap Q_r (kg)	Initial Moisture Content, m_{ci} (% w.b.)	Final average Moisture Content, m_{cf} (% w.b.)	Initial Temp of neat soap	Final Temp of neat soap
1	180	114.9	31.6	31	17	66.5	35.9
2	180	105.3	30.5	35	16	64.2	32.3
3	180	109.3	34.9	33	18	63.1	31.6
4	180	116.5	35.7	29	16	65.7	33.5
Average	180	111.5	33.18	32	16.75	64.9	33.3

DISCUSSION

Design calculation of Mix-kneader components

From TABLE 1, the volume of the kneading trough was determined as 300 L with the length, width, and height as 760 mm, 650 mm, and 500 mm respectively for the rectangular section by considering Equation 1. The length and width were related by L = 1.2W. The basis for the calculation of these kneading trough dimensions was the target design production capacity of 625 kg/hr. Assuming the motor efficiency of 70%, the electric motor capacity required to power the kneading operation was determined as 3.71 kW. Therefore, a 4-kW (5.5 Hp) single-phase AC induction motor was selected since most of the small and medium-scale processors in Uganda operate with a single-phase power supply. A gearbox reducer of speed ratio 30:1 was fixed so as to reduce the speed of the motor to the operating tip speed of 45 rpm (Connelly and Kokini, 2006). The diameter of the main shaft of the Mix-kneader was calculated as 50 mm. This was based on the Maximum Shear Stress Theory of failure employing the equivalent twisting moment Equation 15 and considering a factor of safety of 2 as recommended by (Pedersen, 2018). In order to ensure the comfort of all the machine operators, the design for average was adopted to determine the dimensions of the frame as well as the location of the various component of the machine with respect to the frame. Hence, based on measurements and proportions of the average human body discussed by (Singh and Mehta, 2010) and the dimensions for the different parts of the machine, the overall dimensions of the frame were sized as 600 mm, 700 mm, and 1200 mm for the height, width, and length respectively.

Fig.4 shows that the maximum bending moment occurred at point C (x = 0.35 m), the position of the gear drive system (pinion and big gear). This means that maximum deformation on the shaft occurs at this point due to the overall weight of the gear drive system. The value of the calculated deformation caused on the shaft was 0.005328 mm which does not exceed the maximum allowable deflection 0.01 mm recommended by API Standard. This indicates that failure cannot occur in the shaft and therefore shaft design was safe.

It further guarantees continuous smooth operation of the machine without degradation of the gears and causing noise and vibrations in the moving components.

Fabrication and assembling of the Mix-kneader component

The ease of transportation, dismantling and assembling was purposely considered during the fabrication of the machine. The kneading trough, frame, discharge/exit cute, bearings, sigma blades, gear box, drive shafts and gears, electric motor and the rollers can be separated and carried with ease to the location where the machine is to be used in such a manner that the heaviest single component is the gear box (68 kg) followed by the sigma blades. The assembly can be done by two people. The procedure for assembly is by starting with the frame then fix the kneading trough in which the sigma blades are mounted and fastened by the pillow block bearings, then followed by the drive shafts and gears, and finally connect the gear box and electric motor to the main power transmission shaft. For operational safety, the protective covers are mounted to avoid injuries and clogging of moving parts. The assembling of the machine can be done within 20 – 30 minutes. Compared to other commercially available soap dryers, the machine is portal and mobile since most the dryers discussed by Luis (2016) weigh 850 kg and above. This makes it easier to transport the machine from one processor to another.

Performance evaluation of the developed Mix-kneader

The kneading/drying time increases with increasing feed mass of neat soap (FIGURE 3). This is because the cooling water in the water jacket facilitates higher mass and heat transfer of moisture from the neat soap with small quantities of neat soap than with the big quantities. With big quantities, more cool water is required to circulate through the water jacket for a longer period in order to extract more heat from the neat soap. The Feed capacity of the Mix-kneader is relatively small compared to the dryers used by large-scale processors as discussed by Luis (2016). These commercially available dryers have capacities ranging from 500 L – 2000 L by volume.

The optimum time of 15.5 minutes was in the range of 2 – 20 minutes for most commercially available soap drying machines discussed by Luis (2016). Compared to the current methods used by the small and medium scale processors in Uganda, the Mix-kneader achieves drying at a faster rate. With the current methods used, drying of neat soap to the desired moisture content of 15% is achieved within 24 – 48 hours.

There is fast drying in region B and E (TABLE 2) because they occupy the central part of the kneading trough with high-stress concentration due to the action and shape of the sigma blades. As such, neat soap is sheared, folded, and compressed with greater magnitude in between the two counter-rotating sigma blades compared with other regions in the kneading trough. For each trial experiment made (**Error! Reference source not found.**), the variation of moisture content of dried soap could be attributed to the inconsistencies in initial moisture content of the samples used.

The standard deviation and coefficient of variation can be used to measure the efficiency/uniformity of a mixing/kneading operation. According to (Navas, 2022) by calculating the coefficients of variation using CV = StDev/Mean × 100%, if the CV value is ≤ 10%, the kneading operation is said to be excellent. If the CV value is between 10% – 20%, it is said to be good. If the CV value is between 20% – 30%, it is acceptable and poor for CV > 30%. In TABLE 3, it can be seen that the coefficients of variation (CVs) values are less than 10%, fluctuating between 3.12% and 8.33%. This indicates that the variation of moisture content of the dried soap inside the kneading trough is almost uniform and does not vary widely and that the CV values are within the acceptable range. It also indicates that, a fairly uniform product (dried soap) in terms of moisture content was achieved.

The determined mix-kneader production capacity of 560 kg/hr is relatively lower than that of the commercially available dryers used by large scale processors such as the vacuum dryers with the capacity ranging from 10,000 kg/hr – 15,000 kg/hr, and hot air spray towers and drum/roller dryers capable of drying soap up to 6,000 kg/hr. However, the Mix-kneader capacity is much higher (almost three times) than that of the methods currently employed by the small and medium-scale processors in Uganda. The drying efficiency (83.4%) of the developed Mix-kneader can be attributed to the efficiency of the water jacket surrounding the trough, speed, and shape of the sigma blades. This drying efficiency obtained falls in the range of most commercially available dryers discussed by Luis (2016). The material wastage of 1.31% can be attributed to fabrication errors which facilitated the clogging of some soap material in the spaces that existed on the sigma blades and between the kneading trough walls and the sigma blades ends.

CONCLUSION

A prototype of a Mix-Kneader machine was designed, fabricated, assembled, and evaluated for small and medium scale bar soap production. The Mix-kneader was fabricated using locally available materials. The developed Mix-kneader has a total volume of 300 L and is powered by a 4-kW single-phase AC motor. The Mix-kneader runs smoothly in operation without making too much noise and there was no visual mechanical breakdown during the entire performance evaluation process. At the 'Full' load test, the fabricated mix-kneader accomplished drying of 180 kg of neat soap in an average time of 15.5 minutes compared to 24 hours of the current methods used. The machine has an average capacity of 560 kg/hr with a drying efficiency of 83.4%.

The machine is affordable in terms of cost and maintenance since it was fabricated out of locally available materials. Also, it is reliable and will facilitate and encourage domestic bar soap production at both small and medium production levels.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest for this research.

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