Original Research Article

DEVELOPMENT OF A LOW-COST HAMMER MILL MACHINE FOR FOOD PROCESSING

ABSTRACT

The hammer mill was designed and constructed from locally sourced and available materials for grinding of grain particles such as **SORGHUM**, maize, millet, guinea, etc. into small sizes enough to pass through the holes of the cylindrical sieve positioned beneath the hammer assembly. Hammer mills are used for the pulverization and/or grinding of grains and similar bulk solid materials into smaller particles. Conventional hammer mills consist of a shaft, free swinging hammers, sieve, hopper, electric ~~motor~~motor, and discharge chute amongst other component parts. Hammer mills found mostly within the urban settlements in Nigeria are imported and expensive to acquire by rural farmers thus the need to develop one that can be easily acquired by the rural farmers as well as ease of maintenance. The grinding process is achieved ~~by the use of~~using a hammer in beating the material fed into fine particles; the fineness aimed depends on the beating operation that happens when the Hammers hit the grain particles across the inner walls of the grinding or crushing chamber. The final size of the ground sorghum is a product of the aperture size which ranges from 87µm to 2 mm. The present design was focused on the analytical design of an improved compact hammer mill that employs a single-acting operation to pulverize, move and push out pulverized bulk material particles against gravity through a cyclone. It consists of a loading hopper and tray, low and high-pressure throats, shaft, spacing discs, hammers, axial fan, gate, cyclone, electric motor, bearings and pulley. The fabricated 7.46kw capacity hammer mill is compact, and cost-effective to produce, operate and maintain. Its commercial production and use will be a reprieve to rural farmers as well as promote local content technology in Nigeria. The economic evaluation of the machine revealed that the material worth of US$85.20 was used for its construction. Testing and performance evaluation carried out on the machine showed that the machine had a 98.4% crushing and grinding ~~efficiency~~efficiency.

Keywords: Sorghum*, Grinding*, Design, Hammer mill, Grains, Particles, Sorghum

INTRODUCTION

Sorghum, is a cereal grain plant of the grass family (Poaceae) and its edible starchy seeds. The plant likely originated in Africa, where it is a major food crop, and has numerous varieties, including grain sorghums, used for food; grass sorghums, grown for hay and fodder; and broomcorn, used in making brooms and brushes. In India sorghum is known as jowar, *cholam*, or *jonna*, in West Africa as Guinea corn, and in China as kaoliang. Sorghum is especially valued in hot and arid regions for its resistance to drought and heat [1].

Sorghum is of a lower feed quality than corn (maize). It is high in carbohydrates, with 10 percent protein and 3.4 percent fat, and contains calcium and small amounts of iron, vitamin B_1, and niacin. For human consumption, the gluten-free grain is usually ground into a meal that is made into porridge, flatbreads, and cakes. The characteristic strong flavour can be reduced by processing [2].

Fig 1: The various forms of Sorghum

The grains are edible and nutritious. It can be eaten raw when young and ~~milky, but~~milky but has to be boiled when older. One species, Sorghum bicolor, native to Africa with many cultivated forms, is an important crop worldwide, used for food (in the form of grain or sorghum syrup), animal fodder, the production of alcoholic beverages, and biofuels. Sorghum's cultivation has been linked by archaeological research back to ancient Sudan around 6,000 to 7,000 BP [2].

All sorghums contain phenolic acids, and most contain flavonoids. Sorghum grains are one of the highest food sources of the flavonoid proanthocyanidin. Total phenol content (in both phenolic acids and flavonoids) correlates with antioxidant activity. Antioxidant activity is high in sorghums having dark pericarp and pigmented testa. The antioxidant activity of sorghum may explain the reduced incidence of certain cancers in populations consuming sorghum [1].

Popped sorghum is popular as a snack in India. The popped sorghum is similar to popcorn, but the puffs are smaller. Like popcorn, popping sorghum is done by microwave, in a pot, or other similar ways. It may also be used as a flavoring for clarified butter (ghee) [3].

In China, sorghum flour is used in combination with wheat flour to make noodles and bread. Most varieties are drought- and heat-tolerant, nitrogen-efficient, and are especially important in arid and semi-arid regions, where the grain is one of the staples for poor and rural people. These varieties form important components of forage in many tropical regions. S. bicolor is an important food crop in Africa, Central America, and South Asia, and is the fifth most important cereal crop grown in the world [4].

Global demand for sorghum increased dramatically between 2013 and 2015, when China began purchasing US sorghum crops to use as livestock feed as a substitute for domestically grown corn. China purchased around $1 billion worth of American sorghum per year until April 2018, when China imposed retaliatory duties on American sorghum as part of the trade war between the two countries [4].

Milling of dried grain materials into finer bulk material particles is an age long practice which has been carried out using various methods which include earth stones, forced beating using human effort, mechanical devices by attrition and blenders. Each of these methods has had their various advantages and set back. Increased demand for various materials arising from a growing human population around the world has necessitated technological exploration and improved productivity. This has led to the proliferation of new machineries and optimization of existing ones [4].

The hammer mill, which can otherwise be referred to as Sorghum Miller, is designed for processing, grinding, and sieving all kinds of cereal grains, such as Sorghum, maize, wheat, millet, corn, wheat. Whilst it can also process it can also process non cereal materials such as dry cassava tuber and yam tuber, we would advise that the usage stick to the grinding of cereals. There is a great complexity in the processing of cereals as well which is a major factor in ensuring that the Hammer mill machine be fine-tuned to specific operations and ~~usage..~~usage. The principal procedure is milling; that is, the grinding of the grain so that it can be cooked and rendered into an attractive foodstuff. In ancient time, the cereal grains were crushed between two stones and made into crude cake but the advent of modern automated systems employing steel material such as hammer mill have revolutionized the processing of cereals and their availability as human foods and other purposes. The machine is of hammer mill type. In this case, there is hammer-like projection mounted on a shaft. The hammer revolves at high speed and grinds the materials fed into pieces by beating. Moreover, the machine can mill only the dry materials. The machine is incorporated with a detachable sieving mechanism to ensure fineness of cereal grain ground. The industrial screen - the main components responsible for sieving - is made of wire cloth with aperture sizes ranging from 870 µm to 2 mm [5].

The machine cannot be operated manually. The electrical operation is effected by the use of one horsepower electric motor with speed of 1,400 rev/mm. The machine can handle 5 kg of cereal grains in a single operation lasting 15 min. The entire construction is brought about by locally sourced material thereby making the cost not prohibitive. The machine elements are easily accessible and detachable to facilitate assembling and maintenance process. Due to the cost of importing the Hammer mill machine, there was a necessity to fabricate a machine from locally sourced material for the ease of maintenance, a machine that is easy to maintain, less expensive yet highly efficient machine and we have been able to fabricate such machine [3]

The hammer mill in this regard is a product of improved methods of bulk material grain processing into finer particles by pulverization, grinding and sieving through a solid mesh or forced draft. The machine consists of a shaft on which a set of free-swinging metal weights are attached. It also consists of a loading hopper, milling chamber, bearings and a motor which is connected to one end of the shaft via a pulley and belt and drives (rotates) the shaft and hammers at high speed to effect milling of the grains. Modern day hammer mills are mostly imported from the developed nations into other developing countries like ~~Nigeria hence;~~Nigeria; hence, are quite expensive to acquire, and maintain. Nigeria is a country with vast arable lands mostly around the rural areas where many subsistence and commercial farmers reside. These farmers often farm agricultural produce which require one or more mechanical processing such as milling to convert them from their raw state into semi or wholly finished products like flours made from sorghum, rice, cassava, yam, soya bean etc. the hammer mill is one of such mechanical system which should be amenable to such farmers however, while the imported hammer mills are too expensive for their acquisition, other locally available or improvised methods are either too tedious to use, or are froth with reoccurring problem. Conventional and many locally made hammer mills that have found usage in many farming communities in the country have been observed to have many setbacks and have been a basis for the design of improved and optimized local models of the machine [4].

Documented setbacks of many of the existing locally made hammer mills have been reported by various researchers and they include the following;
Wear and corrosion as a major cause of sieve screen holes' enlargement or burst which then allows passage of larger than desired particles to pass through. After several hours of milling operation, the sieve holes are clogged with a consequential reduction in its efficiency and operating capacity. There is tendency of a build-up of moisture which makes the materials wet and become elastic and therefore absorb most of the impact energy of the hammer without ~~actually breaking~~breaking down to smaller particles. In a bid to proffer solution to the setbacks identified, the authors designed a petrol-powered hammer mill with a dimensionally controlled open gate endless sieve to solve the problem of sieve bust and clogging. A fan was introduced to induce forced convection to dry out moisture. The researchers also introduced a mechanical separator, which rotates at the same speed as the shaft to ensure that all solid particles above certain sizes are blown back into the hammer mill chamber until they are ground or broken by impact into fine particles [6].

1.1. METHODOLOGY

An analytical and adaptive method was employed in the design of the hammer mill. Observatory study of an existing hammer mill and review of some documented research works on hammer mill designs was carried out from which various lapses in design concepts and functions of the machines were inferred. Conceptual design was therefore developed with the incorporation of new features and components integration to correct, ~~improve~~improve, and optimize certain functions of the machine. Materials were sourced ~~locally~~locally, and alternative materials were refined to mitigate problems of unavailability and high cost [7].

Some critical areas of focus on improvement and materials utilized are as follows:~~;~~

- Stainless steel was used as an improvement in hammer mill designs to counter the inefficiencies of Mild steel for food processing machines and avoid the high corrosion tendencies in Mild steel as used by many of researchers. Corrosion of metals is detrimental to food and human health.
- Compactness and simplicity of the new hammer mill employed by integrating all operational components as a single operating unit. This made the work area less bulky and the machine less costly and easy to move from one position to another when required.
- Hopper was fabricated such that it has a horizontal flat tray on which the grains are pushed through a tunnel distance before falling through an opening via a long throat to the milling chamber. This was to prevent fly back or rebound of grain particles and powders from the milling chamber.
- ~~Throat;~~Throat: It was designed and positioned to direct the bulk materials directly inside the milling chamber where it takes direct hit and crush from the hammers.
- ~~Shaft;~~Shaft: The diameter was specifically selected to ensure it has the required strength to resist twisting and bending moments, while the length was to ensure there was enough space to carry the embedded components of discs, hammers, spacers, connecting rods and axial fan. The embedding of the various components listed on the shaft made it an integrated compact system with a single acting operation which makes the machine less bulky, efficient and cost effective to acquire, operate and ~~maintain~~maintain.
- Crushing chamber; it housed most part of the shaft and the entire embedded components. It had an elliptical cut through hole at the opposite end from the loading end through which powder material was pushed out against gravity via an exit throat.
- Electric ~~motor;~~motor: this was the prime driver of the machine. It was selected to have the capacity to drive the shaft and all its embedded components whilst having the capacity to create a push force from the fan required to move the pulverized grain powder up the exit throat against gravity. A 10hp motor was used for effective operation of the machine.
- ~~Bearings;~~Bearings: these were selected according to the type of machine, the design load and shaft diameter
- Structural ~~frame;~~frame: The frame was made to be lower to the ground to reduce vibration and lower centre of gravity for good stability.
- Pulley and belts: a single pulley belt was used to connect the electric motor to one end of the shaft via a driver pulley on the motor and a driven pulley on the shaft.

1.2 Aim of the Project

The aim of this project is to develop an efficient hammer mill suitable for Sorghum grinding out of locally sourced materials and at a reduced production and maintenance cost. This will play a vital role in the cereal production company especially in application to food making for infants and ~~babies~~babies.

1.3 Objectives of the Project

The objectives of this project is to: ~~-~~

1. develop an efficient Food processing Hammer Mill, and
2. carry out performance evaluation of the machine developed in order to determine its functional ~~requirements~~requirements.

1.4 Justification

The problems associated with the existing process of grinding sorghum are enumerated thus:-

1. The old method of sorghum grinding is extremely time-consuming, cumbersome with little output and labour intensive.
2. Cost of buying imported machine is high.

Therefore, the project is to provide an alternative means to the problems highlighted above while still placing emphasis on efficiency of the machine.

1.5 Research Methodology

Extensive review of literatures on the different types of cereals, methods of grinding and existing machines was also carried out. Literatures on cereal grinding machines were read and used. Some experimental grinding processes were done and literature on construction and fabrication techniques was also consulted ~~so as to~~to get a good development which is cheap, made from local materials and with good aesthetics.

The Conceptual design: The conceptual design was based on the principle of design by analysis. The methodology was to introduce special features into the hammer mill so that certain lapses noticed in the convectional hammer mill is reduced to a bearable level. This usually occurs in an enclosed chamber called the crushing chamber. The physical and mechanical properties of the material to be crushed were studied as this would help immensely in the design of various components of the rotor. The engineering properties and some other important parameters must be well known as they are the main factors considered before design of the machine.

The assembly of the machine was also ~~researched~~researched, and the materials selection software (GRANTA) was adequately used. Evaluation and testing of the project work was carried out under a controlled environment of the institute's workshop so that the behaviour of the machine was properly ascertained and its behaviour under other conditions can be predicted.

Vast knowledge of various CAD software (ProEngineer, AutoCAD and Autodesk Inventor) was adequately used in the Modeling and Simulation of this machine and the force analysis was carried out to know its performance under different loading conditions.

1.6 Significance of the Project

The manual method of sorghum grinding is very slow and burdensome which apparently led to the wastage of resources, low output and time consumption. This work aims at increased productivity, optimal performance of the machine and affordability by the Small and Medium scale industries in the country.

1.7 DESIGN CONSIDERATIONS

The design was carried out on the ~~basics~~basis of the safety of the operator. Some other major hazards which may arise in the course of crushing were properly put into consideration. The deflection of the hammers while in operation was also considered in the design. Swinging instead of stiff hammers was used to avoid the rotor or the hammers from getting stocked in case a hammer comes in contact with a material it cannot break on first impact.

1.7.1 BASIC DESIGN

Determination of Shaft Speed

To calculate the shaft speed the following parameters are used.

$$\frac{D_1}{D_2} = \frac{N_2}{N_1} \quad (1)$$

Where:

N_1 = revolution of the smaller pulley, rpm
N_2 = revolution of the larger pulley rpm
D_1 = diameter of smaller pulley, mm
D_2 = diameter of larger pulley, mm

This shaft speed is only obtained when there is no slip condition of the belt over the pulley. When slip and creep condition is present, the value (913.5rpm) is reduced by 4% (Spolt, 1988).

Determination of Nominal Length of The Belt

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) + \left(\frac{D_1 - D_2}{4C}\right)^2 \quad (2)$$

Where:

L = Length of the belt, mm
C = Centre distance between larger pulley and the smaller one, mm
Centre distance minimum, C_{min} was calculated using:

$$C_{min} = 0.55(D_1 + D_2) + T \quad (3)$$

And Centre distance maximum:

$$C_{max} = 2(D_1 + D_2) \quad (4)$$

T = Nominal belt thickness
D_1 = Larger pulley diameter
D_2 = Smaller pulley diameter

Determination of Belt Contact Angle

The belt contact angle is given by equation:

$$\sin^{-1}\beta = \frac{(R-r)}{C} \quad (5)$$

Where:

R = radius of the large pulley, mm
r = radius of the smaller pulley, mm

Determination of the Belt Tension

$$T_2 = \frac{(T_1 - MV_2)}{exp\left[\frac{\mu\alpha}{\sin\frac{1}{2}\theta}\right]} \quad (6)$$

$$T_2 = SA \quad (7)$$

Where :

S = the maximum permissible belt stress, MN/m^2
A = Area of belt

Determination of The Torque & Power Transmitted for the Shaft

$$POWER = (T_1 - T_2)V \quad (8)$$

$$T_r = (T_1 - T_2)V \quad (9)$$

Where:

T_r = Resultant Torque

T_1 & T_2 = Tension in the belt, N

R = Radius of bigger pulley, mm

Determination of Hammer Weight

$$W_h = M_n g \quad (10)$$

Material = Mild Steel

Density = 7.85g/cm3

$$Density = \frac{Mass}{Volume} \left({}^{kg}/_{m^3} \right) \quad (8)$$

Determination Maximum Power Transmissible (Kw)

The maximum power, which the belt can transmit, is given by:

$$P = \frac{0.45}{V^{0.09}} \left[\frac{19.62}{D_o} + 0.765 + 10^{-4} V^2 \right] V$$

Where D_o = equivalent pitch diameter (mm). If F_b is the small diameter factor to account for the arc of contact, then $D_o = d.F_b$ where d = diameter of the driver pulley (mm).

Determination of Hammer Shaft Diameter

$$\sigma_s \quad (allowable) = \frac{M_b Y_{max}}{I}$$

$$\frac{I}{Y_{max}} = Z = \sigma_s = \frac{M_b}{Z} \quad (10)$$

Where:

Y_{max} = Distance from neutral axis to outer fibers

I = Moment of inertia

Z = Section modulus

For solid round bar

Hopper Design

Hopper design is based on a common criterion, which is required for it to function. This criterion is called the *"Angle of Repose"*. Angle of repose is defined as the angle of friction of rest. The hopper designed is a gravity discharge one, and the recommended angle of repose for gravity discharge ranges between 15^0 and 25^0

The volume was estimated from equation;

$$V = \frac{h}{3}\left(A + a + \sqrt{Aa}\right)$$

Where:

h = perpendicular height (mm);

A = Area of the upper opening (mm^2);

a = area of the lower opening (mm^2).

Note that the slant height, l is obtained from the relation, $h = l \cos \phi$ where ϕ is the angle of repose.

Table 1: Design Specifications (Authors' Estimate; 2018)

Components	Assumed Parameters	Design Parameters
Hopper	h=280mm, A= 129,600mm^2, a=12,100mm^2	V=16.92x10^6mm
Speed Ratio	N_1 = 2600 rpm; N_2 = 2267 rpm; d = 102mm	D = 117mm
maximum power	F_b = 1.0; d = 0.102m	P = 4.85kW
Prime Mover	From Shaft, Pulley and capacity	2,600 rpm, 4.85 kW

	design	
Width of pulley	t = 11mm	W ≅ 14mm
Belt Number (*N*)	F_d = 0.98; F_c = 0.8; F_a= 1.2; P = 4.85kW	N = 2.024
Tension, T_1 and T_2	W_1 = 13mm; $\beta = 175^0$; $\theta = 34^0$; W_2= 4.89mm; h = 21.26mm; V = 5.73ms^{-1}	A = 7.16x$10^{-5}m^2$; T_1 = 143.2N; $\alpha_1 = 175^0$; $\alpha_2 = 185^0$; Cl_1 = 64.89; Cl_2=83.02; T_2 = 4.45N
Diameter, *d*, of shaft	Mb = 69.27Nm; Mt = 10.41Nm; Kb= 1.5; Kt = 1.0; $S_s = 55x10^6\ N/m^2$	d = 35mm

2.0 MATERIALS SELECTION PROCEDURE

The considerations contained in this work are aimed at meeting the desired standard as expected for a Sorghum grinding machine. This were the Materials selection procedure that was carried out before each materials was considered appropriate for usage and a final selection was made. The selection of materials for various parts of machine is based on the following factors.

- Strength of the material and rigidity of the machine,
- Availability of the material locally and ease in obtaining them,
- Durability
- Economy / feasibility
- Cost of material and hence production cost with consumer in view,
- Ease of fabrication

S/N	Machine Component	Criteria for Selection	Most Suitable Materials	Materials Selected	Reason for Selection
1.	Shaft	Strength, machine, surface finish, weight, cost, availability.	Mild steel, cast iron	Mild steel	High strength and light weight
2.	Pulley	Weight, good wearing property, availability	Mild steel, cast iron	Mild steel	Availability and weight
3.	Belt Guard	Strength, machinability, surface finish, weight	Mild steel, carbon steel	Mild steel	Surface finish, light weight
4.	Grinding Unit	Weight, good wearing property, availability	Mild Steel, Galvanised Steel, stainless steel	Stainless Steel	Cost, Usage and availability
5.	Bearing	Self-aligning bearing	Standard part	Pillow block bearing	Self-aligning

6.	Hopper	Weight, good wearing property, availability	Mild Steel, Galvanised Steel and stainless.	Stainless Steel	Cost, Usage and availability
7.	Frame (grinding Unit stand and Diesel Engine stand)	Strength, Ability to withstand impact load/stress, availability	Mild Steel, Galvanised Steel	Mild Steel	Strength, Ability to withstand impact load/stress and availability

Table 2: Materials Selection Procedure

3.0 MACHINE DESCRIPTION

The machine is being driven by a prime mover with a rated power output of 4.85 kW and a speed of 2600 RPM. The prime mover is connected to the shaft driving the hammers by a Pulley - belt drive system. The machine comprises of four major parts, the hopper, the crushing chamber, machine frame and the prime mover. The Sorghum is fed into the hopper, with the feed control locked. The feed control is then released gradually to allow flow of Sorghum into the crushing chamber. There in the crushing chamber, the Sorghum ~~is been~~has been beaten by set of hammer mills to reduce the sizes of the feed Sorghum. The reduced Sorghum flows out of the crushing chamber through the delivery chute connected to the bottom of the crushing chamber.

3.1 ELECTRIC MOTOR

The Electric motor was selected based on the speed and required power output for the smooth and efficient operation of the machine. The specifications of the diesel engine as available on its tag are:

Fig 2: Picture of the Coupled Hammer Mill Machine

DESCRIPTION	DATA
Power	5.75 Kw
Speed	2800rpm

Table 3: Electric Motor Specifications

Fig 3: Picture of the Uncoupled Hammer Mill Machine
to show the grinding chamber (hammer mills and compartment)

PERFORMANCE EVALUATION

Sorghum was used to determine the performance evaluation of the machine. The testing apparatus used were the digital ~~stop watch~~stopwatch and weighing balance. 5kg of sorghum was used as the sample, and this was fed into the crushing chamber of the machine through the feed hopper. The time taken to crush the sample ~~i.e.~~i.e., the sample to fully discharge was ~~noted~~noted, and the weight of the crushed sample taken. The process was repeated for samples of weight 10kg, 15kg, 20kg and 30kg with the results obtained as follows;

Trials/Test	Weight input (kg)	Time Taken (min)	Weight output (kg)
1	5	6	4.7
2	10	10.5	9.5
3	15	16.7	14.85
4	20	23.3	20
5	25	29.2	24.5
Average	**75**	**85.7**	**73.55**

Table 4: Performance Evaluation of Machine

The performance criteria tested for, were:~~;~~

a. Grinding capacity (GC), and
b. Grinding efficiency (GE).

Crushing Capacity (CC): The grinding capacity is the rate at which the machine grinds in kilogram per hour and this was calculated as:~~;~~

$$GC = \frac{M}{t}$$

Where~~;~~:

GC = Grinding Capacity (kg/hr)

M = Average mass of Sorghum loaded into the hopper (kg)

T = Average time taken to complete the grinding (hr.)

Considering the results obtained from the performance of the machine, the capacity of the machine (GC) is obtained as follows:~~;~~

$$GC = \frac{M}{t}$$
$$GC = \frac{73.55}{0.714}$$
$$GC = 103.01kg/hr \approx \mathbf{103kg/hr}$$

This means this machine has the capacity of processing 103kg/hr of Sorghum which makes it a good machine for usage.

Crushing Efficiency (CE): This is defined as the ratio of crushed sorghum to the mass of sorghum loaded to the machine and is calculated as:;

$$CE = \frac{average\ mass\ of\ crushed\ sorghum}{average\ mass\ of\ loaded\ sorghum} x\ 100\%$$

Where $CE = Crushimg\ Efficiency$

$$average\ mass\ of\ crushed\ sorghum = 73.55kg$$

$$average\ mass\ of\ loaded\ sorghum = 75kg$$

$$CE = \frac{73.55}{75} x\ 100\%$$

$$\mathbf{CE = 98.10kg}$$

4.3 CONCLUSION

The sorghum hammer mill designed and fabricated in this work was aimed at reducing the grain size of sorghum to finer sizes for cereal production. The performance evaluation of the produced machine showed it works at an efficiency of 98.10%, thereby making the fabricated hammer mill efficient. The materials selected for the development of the machine are locally available thereby making the machine easy assessable and affordable.

The nutritional hazards associated with the use of conventional hammer mills is virtually eliminated in the new hammer mill. Thus, there is no health hazard experienced by the operation of the new machine. Furthermore, the new hammer mill would reduce working losses, reduce production downtime, give nutritional advantages, enhances greater consumer choice and it reflects a more effective response to changing market requirements and increases better working capability of the Machine.

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