Advances in Engineering Design Technology Vol. 2, 2020 pp. 80-88 ISSN-2682-5848

NIPES

Advances in Engineering Design Technology

Journal homepage: www.nipesjournals.org.ng

Design and Fabrication of a Compact Single Acting Hammer Mill

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Article info

Received 17 November 2020
Revised 03 December 2020
Accepted 05 December 2020
Available online 07 December 2020

Keywords:
Mill, Bulk material, Compact, Single acting, Cyclone

https://doi.org/10.37933/nipes.a/2.2020.7

https://nipesjournals.org.ng

Abstract

A compact single acting hammer mill was designed and fabricated using locally sourced materials. 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 shaft, free swinging hammers, sieve, hopper, electric motor and discharge. Hammer mills found mostly within the urban settlements in Nigeria are imported and expensive to acquire by rural farmers. Conventional hammer mills have some setbacks which include sieve screen wear and blockages, moisture build up in pulverizing chamber, bulkiness and production of undesired coarse particles. The present design was focused on 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.Test procedures carried out using the machine showed that fine particles sizes (between 400µm-600µ) were produced from pulverization of dried bulk food material such as cassava, maize, plantain. The fabricated 7.46kw capacity hammer mill is compact, 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.

1. Introduction

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. 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; 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 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. Documented setbacks of many of the existing locally made hammer mills have been reported by various researchers and they include the followings;

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. [1]. 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 buildup of moisture which makes the materials wet and become elastic and therefore absorb most of the impact energy of the hammer without actually 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.

A hammer mill with end suction was designed by [2]. The authors cited some drawbacks in conventional hammer mill design which include moisture build up, sieve deterioration, particle size limitation greater than 400µm, high cost of screen maintenance and environmental pollution resulting from bulk material powder escape. In their bid to solve the aforementioned drawbacks, they incorporated an endless open gate sieve in their design to eliminate sieve screen. They also incorporated a fan for moisture removal. A mechanical separator rotating at the speed of the shaft was used to blow larger particles back for re-pulverization. To minimize dust pollution, a sedimentation chamber with long tubes was installed to redirect the dust into the milling chamber.

A hammer mill with a 1 horsepower capacity which could process a 5kg of cereal in 15 minutes was designed and produced by [3]. The focus of his designed was the use of locally sourced materials for the production in order to reduce cost of production and maintenance. He also asserted that the machine could be dis-assembled to ease maintenance.

2. 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 and optimize certain functions of the machine. Materials were sourced locally and alternative materials were refined to mitigate problems of unavailability and high cost. Some critical areas of focus on improvement and materials utilized are as follows;

i. Stainless steel was used as an improvement in hammer mill designs where in corrosion prone mild steel is used by many of researchers. Corrosion of metals is detrimental to food and human health.

ii. 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.
iii. Hopper of the machine was made from stainless steel plate of 2mm thickness. It 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.
iv. Throat; the throat was a 600mm long 5 by 5 inches' square pipe made from 2mm thick stainless steel plate. 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.
v. Shaft; this was a 40mm diameter stainless steel rod with a length of 400mm. 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
vi. Embedded shaft components; these included the cooling and extractor fan, the 3 in number 120mm diameter circular discs, the 4 x 3000mm connecting rods and the 48 numbers hammers
vii. Hammers; the hammers were 5mm thick, 40mm wide and 80mm long stainless steel plates that were totaling 48 in numbers. Holes of 16mm diameter were drilled in them at about 10mm from one end where they were inserted on the connecting rods.
viii. Crushing chamber; this was a 280mm diameter by 4mm thick by 400mm long stainless steel cylinder it was blocked at both ends with a 2mm thick stainless steel plate, however; one of the plate was bolt fastened to one of the side for ease of disassemble and maintenance. 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.
ix. End suction Fan; the use of an end suction fan made of 3 number 3mm thick steel plates measuring 120mm by 80mm and separated at 60^0 interval ensured that there was a supply of air to cool the milling chamber. The fan also created a draft air force to recirculate the grains for proper crushing, and re-grinding against the internal milling chamber wall by attrition. The attrition was aided by a small clearance of about 5mm between the fan edge and the internal cylinder wall. Fine particles are finally forced up an exit throat against gravity by the fan and through a cyclone. The incorporation of the fan eliminates the use of sieve screen and hence hole clogging, enlargement and burst are eliminated. It also reduces and makes easier maintenance of the mill as it was not welded to the shaft directly but to a hollow pipe which was worn on the shaft.
x. Cyclone; the cyclone is a particle separation and discharge medium that was incorporated in the hammer mill. On forceful pushing of the fine particles at high pressure through the exit throat by the fan, the particles find way into the cyclone and flow in an involute path in the cyclone at a reduced pressure before exiting through a narrow throat to a receiving bag or ware. The cyclone was designed as a cylinder welded to a cone of the same base diameter of 350mm.
xi. Electric 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 10 horsepower motor was used for effective operation of the machine.

xii. Bearings; these were selected according to the type of machine, the design load and shaft diameter
xiii. Structural frame; this was made from 4inch mild steel angle bar of 5mm thickness. The frame was made to be lower to the ground to reduce vibration and lower center of gravity for good stability.
xiv. 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.

The graphical detailing of the new hammer mill with its components is shown in Figures 1 and 2

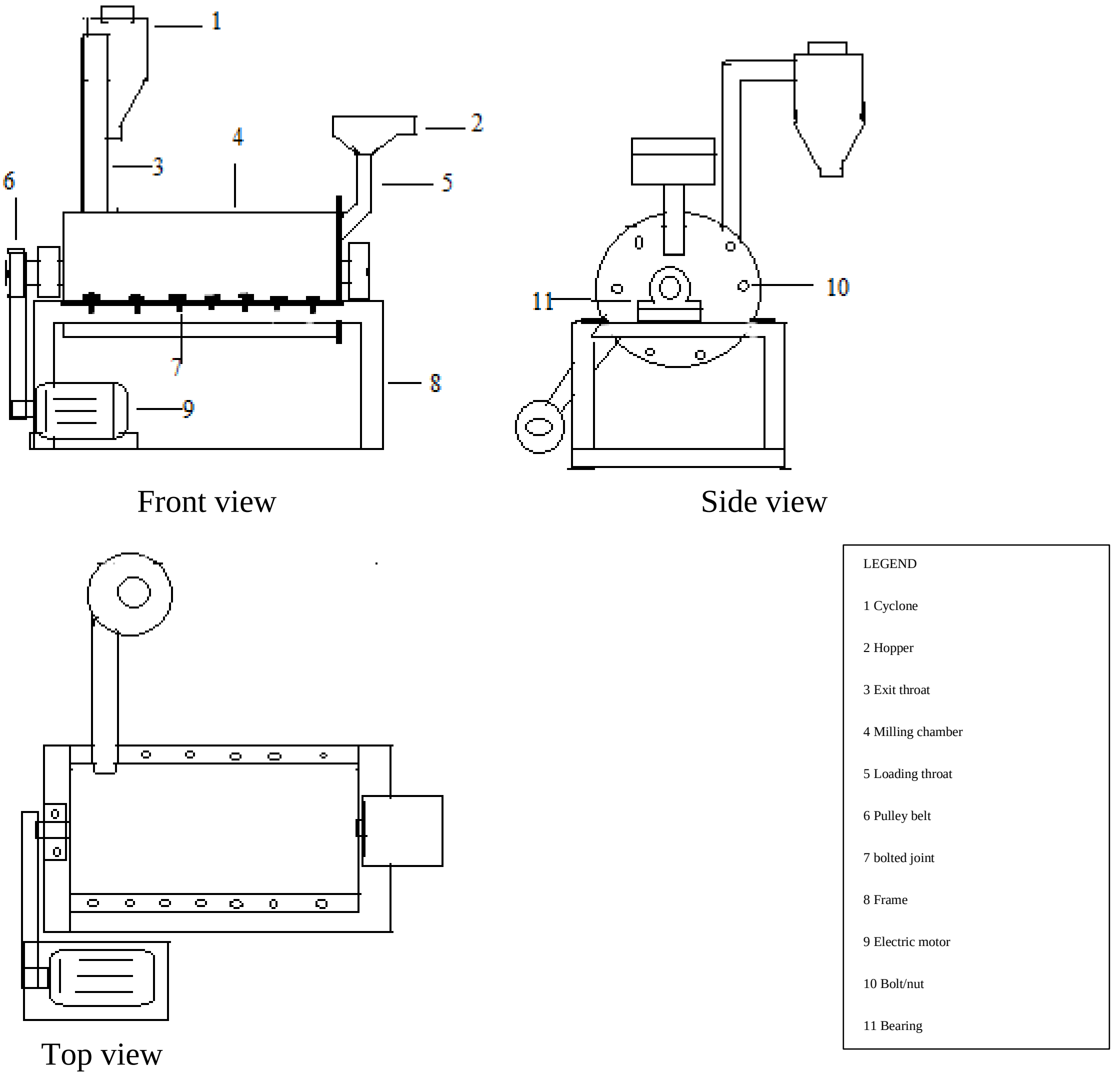

Figure 1 Orthographic detail of the compact hammer mill

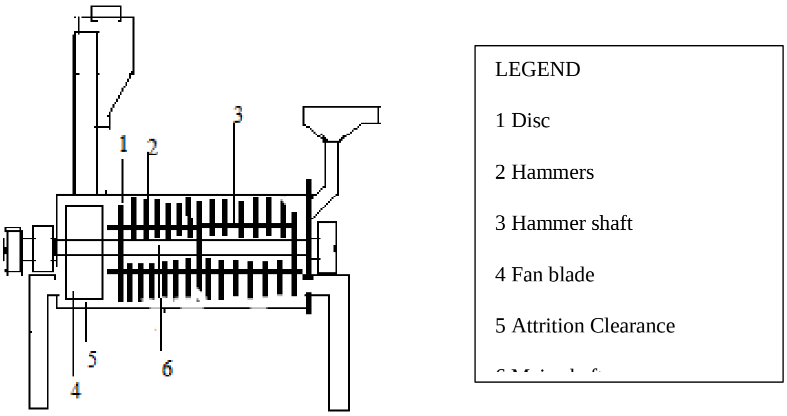

Figure 2 Sectioned view of the hammer mill

2.1. Detailed Design

2.1.1. Determination of crushing force F_c of the hammers

F_c which is centrifugal must be greater than the force required to crush hardest bulk grains to be milled with the machine.

$$F_c = \frac{mv^2}{r} = m_t r\omega^2 \qquad (1)$$

Where; m= total mass of the hammers (kg) = density ρ x volume υ of the rectangular hammer
v= rotational speed of the shaft (rpm), ω = angular velocity rad/m, r = radius of curvature of path of rotation.
The volume of the hammer is a function of its length, width and thickness.
The minimum width w_h of the hammer which can withstand the centrifugal force at impact is expressed as;

$$W_h = d_h + \frac{F_h}{t_h \sigma_h} \qquad (2) \qquad [4]$$

Where; F_h = centrifugal force of hammer, d_h = diameter of hammer, t_h = thickness of hammer, σ_h = working stress on hammer.
If v = number of revolution N_2 of the shaft, then it follows that;

$$N_2 = \frac{D_1 N_1}{D_2} \qquad (3) \qquad [5]$$

This shaft speed is maximum at 3600rpm on no load and no slip condition of the belt over the pulley. If slip and creep condition is present, the value (3600 rpm) is reduced by 4% [6]

Where; D_1 diameter of the motor pulley (m), N_1 revolution of the motor (driver) pulley
D_2 diameter of the shaft (driven) rotor.

2.1.2. Shaft diameter D_2

This is expressed as $$D_2^3 = \frac{16}{\pi S_s}[(K_b M_b)^2 + (K_t M_t)^2]^{1/2} \qquad (4)$$

Ss = allowable stress MN/m^2, K_b = Shock and fatigue factor for bending moment, K_t = shock and fatigue factor for torsional moment. K_b and K_t = 2 for suddenly applied shock loads
M_b = bending moment, N_m and M_t = torsional moment, N.

2.1.3. Bulk material dynamics

The hammers rotate at high speed and torque from a fixed position without obeying hooke's law of elasticity. This causes a disturbance on the bulk materials which are dispersed at a velocity v_m expressed as follows:

$$V_m = \left(\frac{2F_h r_h}{M_n N_n}\right)^{1/2} \qquad (5) \quad [5]$$

Where; m_m = mass of bulk material, N_m = number of material impacted, F_h = centrifugal force r_h = radius of hammer.

2.1.4. Fan blade design

The fan consists of 3 blades separated at 60^0 apart and connected axially to the shaft. The bending and shearing forces of the rectangular blades are expressed as follows;

$$F_b = \sigma_b A = \frac{M}{Z}(lwt) \qquad (6)$$

Where; F_b = bending force, F_s = shear force, σ_b = bending stress, t_b = thickness of blade, w = width of blade, l = length of blade, τ = shear stress on blade

2.1.5 Length L of Pulley belt

$$L = \frac{\pi}{2}(d_1 + d_2) + 2x + \frac{(d_2 - d_1)^2}{4x} \qquad (7)$$

Where; d_1 = diameter of motor pulley, d_2 = diameter of shaft pulley and x = center distance between pulleys.

2.1.6 Tension on belt

Tension is required to enforce a grip on the pulleys for effective shaft rotation. The centrifugal tension of the belt is expressed as;

$$T_c = m\omega^2 \qquad (9)$$

But the maximum tension in belt is T = SA

Where; S is maximum permissible shear stress MN/m^2, A = area of belt

A = belt breadth (b) x belt thickness (t)

For the mass per unit length of belt, m = btρ

Where; ρ = density of the material of the belt

Tension on the tight side of the belt is $T_1 = T - T_c$

Tension on the slack side of belt $T_2 = 2.3\log(T_1/T_2) = \mu.\theta$ (10)

Where; μ= coefficient of friction between belt and pulley, θ= $(180^0 + 2\alpha)$ is the angle of contact between belt and pulley.

α = ratio of the difference in radii of the open belt pulleys to the pulley center distance

$$\sin \alpha = \frac{r_1 - r_2}{x}$$

2.1.7 Power (P) required to drive the shaft

This was supplied by the prime driver (electric motor). It is expressed as

$$P = (T_1 - T_2)v = T\omega \qquad (11)$$

2.1.8 Cyclone design

The cyclone cylinder circumference = 2πr (12)

This equal to the length of arc (base) of the cone = $\frac{\theta}{360}$ x 2πr

Total surface area of the cyclone = $2\pi rh + \pi r^2 + \pi rl$ (13)

$= \pi r(2h + r + L)$

Where; r = base radius of cylinder and cone, h_1 = height of cylinder, l = height of cone

Volume of cyclone = $\pi r^2(h + \frac{1}{3}l)$ (14)

2.1.9 Crushing Efficiency E_c

This is expressed as $E_c = \frac{material\ output}{material\ input} \times 100$ (15) [3]

3. Results and Discussion

The designed hammer mill was successfully fabricated using locally sourced materials at a cost of 200000 Naira. The cost of acquiring a hammer mill of equivalent capacity from foreign sources such as China and Europe range between 800000 and 1500000 Naira. While it takes between 3 to 5 days to readily produce the locally sourced hammer mill, it often takes weeks and months to have an imported hammer mill delivered to Nigeria from Europe and China. Significant design parameters as calculated are shown in Table 1. The fabricated hammer mill was tested by using it to pulverize various quantities of dried maize, cassava and plantain chips. The performance evaluation of the machine shown in Table 2 was carried out based on three key operational output which include

i. Particle size of pulverized bulk material
ii. Materials balance of bulk material
iii. Duration of pulverization

Table 1 Results of the calculated parameters

Parameters	Symbol	Value	Unit
Centrifugal force exerted by the hammer	C.F	3473	N
Shaft Speed	N_2	2880	rpm
Diameter of main shaft	d	40	Mm
Length of Belt	L	1235	mm
Belt Contact Angle	B	3.48	Degree
Angle of wrap between belt and pulley	A	199.2	Degree
Tension in the slack side of belt	T_2	194	N
Tension in the tight side of belt	T_1	464	N
Power transmitted to the shaft	P	7460	W
Weight of hammer	W_{hammer}	1.25	N
Diameter of hammer shaft	D	15	mm
Weight of hammer shaft	W_s	0.243	N
Bending force of blade	F_b	101.7	N
Maximum bending moment of blade	$M_{b\ (max)}$	2034	Nmm
Total surface area of material of cyclone	A_{ts}	1.2	M^2
Volume of cyclone	V_c	0.064	M^3

Table 2. Operational output of fabricated hammer mill

Material	Trials	Mass of bulk material before milling (kg)	Mass of bulk material after milling (kg)	Time (min)	Particle size remark	Mill efficiency (%)
Dried cassava	1	10	9.55	4.57	Fine (400µm-600400µm)	
	2	10	9.6	5.0	Fine (400µm-600400µm	
Averages		10	9.57	4.8		96
Dried plantain	1	10	9.7	4.5	Fine (400µm-600400µm)	

	2	10	9.62	4.51	Fine (400µm-600400µm	
Averages		10	9.65	4.5		97
Dried maize	1	10	9.5	5.05	Fine (400µm-600µm)	
	2	10	9.5	5	Fine (400µm-600µm)	
Average		10	9.5	5.03		95

From the result as shown in Table 2, it was observed that the machine pulverized all three bulk food materials to fine particle sizes within the particle sizes of (400µm-600µm). This was made possible by the impact action of the hammers, attrition force between the fan blade and the bulk materials and the end lift suction of the fan through the endless sieve (gate). Time variation observed in the milling of the three bulk materials showed that it took lesser time for the dried plantain chips to be pulverized owning possibly to its softer texture. The crushing efficiency of the machine was also highest with the plantain chips milling at 97% compared to the dried cassava and maize which took a bit longer time to pulverize at lower efficiencies of 96% and 95% respectively. However; the efficiency of the fabricated hammer mill for maize milling was slightly higher than that recorded by [3] for maize milling which was put at 94%. The dried maize had the longest pulverization time. The bulk material mass balance as shown by the input and output product showed that there was minimization in losses owning to the closed single operation of the machine and the elimination of a sieve screen which could have clogged up the free passage of the pulverized particles. The fabricated hammer mill is shown in Figure 3.

Figure 3 the Fabricated Compact simple acting Hammer mill machine

The fabricated hammer mill is compact and can conveniently be set up in production areas with limited work spaces. The elimination of sieve screen and separation chamber contributed to its compact feature as compared to the presence of sieve screen in hammer mill produced by [3] and the presence of separation chamber in hammer mill produced by [2].

4. Conclusion

The fabricated compact single action hammer mill with forced draft suction was designed and fabricated to achieve key objectives of simplicity, low cost of production, fine particle production, reduced particle loss and pollution minimization. Test carried out and results achieved showed that the objectives were greatly achieved. Conventional hammer mills which incorporates sieve screens encounter problems of screen clogging and bust as well as material losses and pollution. Other designs by various researchers have been found to be too bulky with attached blowers and housing, while others tend to be compartmentalized with separate chambers and routes for milling and separation of fine and coarse particles. Bulky and compartmentalized mills often occupy larger working space. The new fabricated hammer mill made efforts to eliminate these short falls by designing the machine as a compact single unit system where all tasks are achieved by a single operation. The fabricated hammer mill is a promising design that can promote the Nigerian local content initiative as well as enhance food production, revenue generation and job creation in rural and urban areas of the country.

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