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Design, Construction and Performance Evaluation of a Modified Cassava Milling Machine

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Abstract: This study on the design and construction of a modified cassava milling machine was done, owing to the inability of existing mills to meet the demand of cassava flour in bakery industries. Rational design by drawing and calculations and fabrication in the Centre for Industrial Studies (CIS) FUTO were used to bring this mill to reality. The modified cassava milling machine has a milling efficiency of 82.3%, it is dust free and self-cleaning and due to proper air circulation does not destroy the cassava flour produced by overheating. The cassava flour produced was found to have a fineness modulus (fm) of 0.31, Uniformity index (U) of 0: 1: 9 (coarse: medium: fine) and effective size (D_{10}) of 0.075 mm which is better than that produced by an existing mill (hammer mill) of fineness modulus (fm) 2.32, uniformity index (U) of 4:1:5 and effective size (D_{10}) of 0.085 mm.

Keywords: Cassava, flour, hammer mill, milling machine

INTRODUCTION

Cassava (*Manihot specie*) is a tuber crop grown in many parts of the tropics. In Nigeria, it is known by many names such as ‘akpu’ by Igbos, ‘eye’ by Yorubas, ‘Igari’ by Ikas and ‘bobozi’ by Ishans. Nutritionally, cassava contains potassium, iron, calcium, vitamin, folic acid, sodium, vitamin C, vitamin B-6 and protein (IITA, 2005).

Cassava can be processed into many products in Nigeria (Odigboh, 1985). Some of the products are garri, “abacha”, flour, nodules, starch and animal feed. The unit operations involved in processing cassava is shown in Fig. 1.

The Federal Government of Nigeria gave a directive that all baking industries across the country should add 10% of cassava flour to bread. This directive by the Federal Government on baking industries made the demand for cassava flour to rise.

The traditional or indigenous way of producing cassava flour in our rural areas, that is, by pounding the dried chips in a mortar with a pestle and sieving it with a screen, can no longer meet the demand for the cassava flour. Also, the existing mills such as the attrition mill, the hammer mill used by some industries show some inefficiency. Such inefficiencies are:

- Inability to produce uniform grind of the cassava flour.
- Time taken to crush material to the size of the screen as in the hammer mill.
- Contamination of cassava flour due to multi-purpose nature of the mill, particularly in non-specialized production processes.

This research is aimed at developing a modified cassava milling machine that can address nearly all the concerns of the existing milling machines.

Hammer mills for fine pulverizing and disintegration are operated at high speeds. The rotor shaft may be vertical or horizontal, generally horizontal (Perry and Don, 1998). The shaft carries hammers, sometimes called beaters. The hammers may be T-shaped element, bars, or rings fixed or pivoted to the shaft or to disks fixed to the shaft. The grinding action results from impact and attrition between lumps or particles of the material being ground, the housing and the grinding elements. It also consists of a heavy perforated screen (Henderson and Perry, 1982) which can be changed. Though it is a versatile machine and its hammer wear does not reduce its efficiency, yet the power requirement is high and it does not produce uniform grind. Common types available in the industry include the Imp Pulveriser, the Mikro Pulveriser, the Fitz Mill, etc.

Another class of size reduction machines is the Ring-roller mills. They are equipped with rollers that operate against grinding rings (Perry and Don, 1998). Pressure is applied with heavy springs or by centrifugal force of the rollers against the ring. Either the ring or the rollers may be stationary. The grinding ring may be in a vertical or a horizontal position. Ring-roller mills also are referred to as ring roll mills or roller mills or medium-speed mills.

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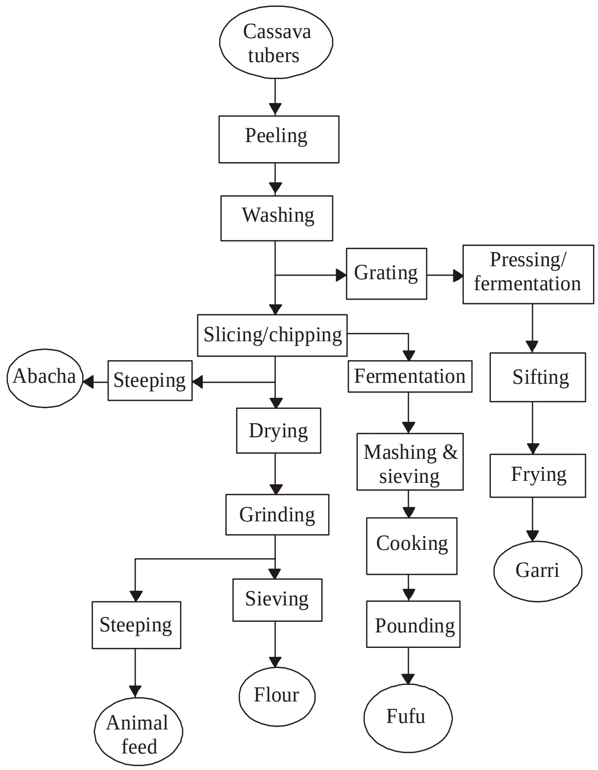

Fig. 1: Unit operations in processing cassava into different products (Odigboh, 1985)

Ring-Roller mills are more energy efficient than hammer mills. The energy to grind coal to 80% passing 200 mesh was determined as: hammer mill-22hp/ton; roller mill-9hp/ton (Luckie and Austin, 1989). Common types available include the B/W Pulveriser and the Roller Mill.

The third class available is the Attrition Mills. The disc attrition which is sometimes called the Burr mill consists of a set of two hard surfaced circular plates pressed together and rotating with relative motion (Onwualu *et al*., 2006). Stones are replaced by steel disks mounting interchange metal or abrasive grinding plates rotating at higher speeds, thus permitting a much broader range of application. They are used in the grinding of tough organic materials, such as wood pulp and corn grits (Perry and Don, 1998). Grinding takes place between the plates, which may operate in the vertical or horizontal plane. The material is fed between the plates and is reduced by crushing and shear. Though the power requirement is low, operating empty may cause excessive burr wear and a lot of heat is generated during shearing action.

The objective of this study is the development of a modified milling machine which combines both an impact and shearing milling action with a pneumatic conveying and clarifying action. The combined action is intended to lead to lead to efficient milling of cassava into fine powder. Unlike the normal hammer mill, it does not use a screen classifier; rather it employs air classifier in which the fine product is carried in the air-stream through the blower's chamber. Also, less time is required for pulverization and due to the air-tight nature, dust spillage is minimized. The air circulating in the machine helps to cool the processed flour which makes the flour a High Quality Cassava Flour (HQCF).

MATERIALS AND METHODS

This study was conducted at the Engineering workshop of Federal University of Technology, Owerri in 2010. All materials are locally sourced. Design is the transformation of concepts and ideas into useful machinery (Bernard *et al*., 1999). The procedures in the design and construction of the modified cassava milling machine are explained.

Theoretical design and material selection: The materials for the construction of the modified cassava milling machine are: the shaft, pulley, belt, electric motor, the bearing, the mild steel plates, mild steel angle bars and mild steel cylindrical tube.

These materials were selected based on the power requirement in the milling of dried cassava chips to flour. By mere feeling, it was found that cassava chips when dried to moisture content of 5% (wb) can be crushed into powder with the human fingers. Thus, the power required for its milling is low.

Table 1: Dimensions of standard V-belts (Khurmi and Gupta, 2004)

Types of belt	Power ranges in kw	Minimum pitch diameter of pulley (D) mm	Top width (b) mm	Thickness (t) mm
A	0.7-3.7	75	13	8
B	2-15	125	17	11
C	7.5-75	200	22	14
D	20-150	355	32	19
E	30-350	500	38	23

Selection of electric motor: An electric motor of the following specification on the name plate was selected:

Power, P = 3.7 kw (5 hp)
Rational speed, N = 1440 rpm
Phase = Single
Frequency = 50 Hz

Selection of transmission drives: The power transmission drives used for the machine are belt and pulley.

- **Design for pulley or sheave:** The rotor's pulley diameter was selected using the equation for speed ratio shown in Eq. (1):

$$D_r = D_m N_m / N_r \tag{1}$$

where,
N_m = Rotational speed of electric motor = 1440 rpm
D_m = Measure diameter of motor's pulley = 3 in
Ns = Rotational speed of rotor (rpm)

The speed of the rotor was chosen as 1080 rpm due to the pneumatic conveying of material in the modified cassava flour mill. The speed must be high enough to generate air of velocity greater than the critical velocity of the cassava flour to be conveyed and discharged upwards.

- **Design for belt:**
  - **Selection of belt type:** Based on the power transmitted (3.7 kw) and according to the Indian standards (IS: 2494-1974), belt type A was selected from the Table 1.
  - **Calculation of belt length, L:** Khurmi and Gupta (2004) developed equation for calculation of belt length as shown in Eq. (2):

$$L = \frac{\pi}{2}(D_1 + D_2) + 2x + \frac{(D_1 + D_2)^2}{4x} \tag{2}$$

where,
L = Length of belt (in)
D_1 = Smaller sheave diameter = D_m (3 in)
D_2 = Larger sheave diameter = D_r (4 in)
x = Centre distance of pulleys (in).

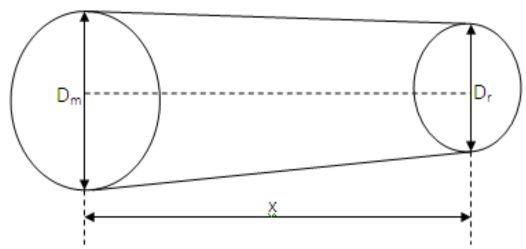

Fig. 2: Open belt drive

These parameters are represented in Fig. 2.

Design for shaft: A shaft is the rotating machine element which transmits power from one place to another (Khurmi and Gupta, 2004). The shaft of the cassava flour machine which is rotating the beaters and fan will be subjected to twisting moment only.

For a shaft subjected to twisting moment only, the diameter of the shaft was obtained by using the torsion equation given in Eq. (3):

$$T = \frac{\pi}{16} x \tau x d^3 \tag{3}$$

where,
T = Twisting moment (Nm)
τ = Torsional shear stress (N/m^2) = 42 MPa (Khurmi and Gupta, 2004).
d = Diameter of shaft (m)

Khurmi and Gupta (2004) developed equation for determination of Twisting moment (T) for a belt drive as shown in Eq. (4):

$$T = (T_1 - T_2) R \tag{4}$$

where;
T_1 = Tight side tension (N)
T_2 = Slack side tension (N)
R = Radius of pulley (m)

Determination of T_1 and T_2: From Eq. (5), the tight side tension was gotten as:

$$T_1 = T_m - T_c \tag{5}$$

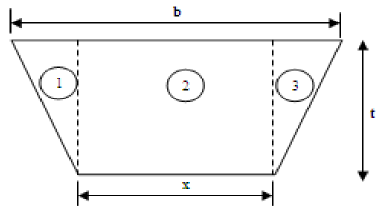

Fig. 3: Cross-section of V-belt

where,
T_m = Maximum tension in belt (N)
T_c = Centrifugal tension (applicable for belt running at high speed).
T_m = Maximum stress x cross-sectional area of belt

$$T_m = \sigma a \tag{6}$$

Determination of belts cross-sectional area, a: The cross-sectional area of the belt was calculated by considering Fig. 3.

From Table 1, top width, b = 13 mm; thickness, t = 8 mm and by calculation, the bottom width x was got as 8 mm.
Thus,

$$\begin{pmatrix} Area\,of \\ triangle\,1 \end{pmatrix} \quad \begin{pmatrix} Area\,of \\ triangle\,2 \end{pmatrix} \quad \begin{pmatrix} Area\,of \\ triangle\,3 \end{pmatrix} \tag{7}$$

Area of belt, a = + +

$$a = \frac{t}{2}\left(\frac{b-x}{2}\right) + xt + \frac{t}{2}\left(\frac{b-x}{2}\right) \tag{8}$$

$$a = \left(\frac{b-x}{2}\right)t = xt \tag{9}$$

Maximum allowable stress of belt, σ = 2.8 MPa (2.8 N/mm^2)
Also, centrifugal tension, T_c was determined using Eq. (10):

$$T_c = mV^2 \tag{10}$$

Table 2: Density of belt materials (Khurmi and Gupta, 2004)

Material of belt	Mass density in kg/m^3
Leather	1000
Canvass	1220
Rubber	1140
Balata	1110
Single woven belt	1170
Double woven belt	1250

where m = mass of belt per unit length. It was calculated using:

$$m = \rho a \tag{11}$$

ρ = density of belt material (Rubber) (m^3/s)

From Table 2, the density was found to be 1140 kg/m^3
Also, V = linear speed of belt given as:

$$V = \pi DN / 60 \tag{12}$$

For a V-belt drive, the tension ratio is given by the Eq. (13) as:

$$\frac{T_1 - T_C}{T_2 - T_C} = e^{\mu\theta \operatorname{cosec}\alpha/2} \tag{13}$$

where, μ = Coefficient of friction between belt and pulley
θ = Angle of wrap (radian)
α = Groove angle = 34° (Table 2)

From Table 3, the coefficient of friction between belt (rubber) and pulley (dry cast iron) was taken as 0.30.

By considering the small pulley, the angle of wrap, θ was calculated using the Eq. (14):

$$\theta = \left[180 - 2\sin^{-1}\left(\frac{D_1 - D_2}{2x}\right)\right]\frac{\pi}{180} rad \tag{14}$$

Power transmitted by belt, P_b: The power transmitted by one belt was calculated using Eq. (15):

$$P_b = (T_1 - T_2)V \tag{15}$$

Table 3: Coefficient of friction between belt and pulley

	Pulley material				
	cast iron, steel				
Belt material	dry	wet	greasy	wood	leather face
Leather oak tanned	0.25	0.2	0.15	0.3	0.38
Leather chrome tanned	0.35	0.32	0.22	0.4	0.48
Convass-stitched	0.20	0.15	0.12	0.23	0.27
Rubber	0.30	0.18	-	0.32	0.40
Balata	0.32	0.20	-	0.35	0.40

Number of belts required, n.: The number of belts required to transmit 3.7 kw power from electric motor was calculated using Eq. (16) as:

$$n = \text{Motor power /power per belt} \qquad (16)$$

(Khurmi and Gupta, 2004)

Selection of bearing: Ball rolling contact bearing of standard designation 307 was selected for the cassava milling machine. This selection was based on the type of load the bearing will support when at rest and during operation and also based on the diameter of the shaft.

The designation 307 signifies medium series bearing with bore (inside diameter) of 35 mm (Khurmi and Gupta, 2004):

Principles of operation of machine: Certain principles were considered during the design and fabrication of the modified cassava milling machine. Such principles were in designing the milling action and the conveying action. The principles are size reduction principle and pneumatic conveying principle.

Principle of size reduction: The cassava milling machine applies the principle of shear and impact in the reduction of size of the dried cassava chips. The energy required to produce the small change (dx) in the size of the dried cassava chips was obtained by using Eq. (17) (Onwualu *et al*., 2006):

$$dE/dx = k/x^n \qquad (17)$$

where, k = a constant, n = an exponent

For fine grinding, Rittinger's law (n = 2) was applied on Eq. (17) to yield:

$$dE/dx = -k_1/x_2 \qquad (18)$$

By substituting variables and integrating Eq. (18) between x_2 and x_1, the energy equation was developed as shown by Eq. (19):

$$E = k_1[1/x_2-1/x1] \qquad (19)$$

where,
x_1= Average initial size of the material
x_2= Average final size of the product
E= Energy per unit mass
k_1= Rittinger's constant

Principle of pneumatic conveying: Pneumatic conveyors are mostly suited for small seeds and products in powdery form, such as rice and flour (Onwualu *et al*., 2006).

Due to light weight of the cassava flour, pneumatic system consisting of a fan which increases the speed of the air was incorporated to the machine's rotor.

The fan at the top of the milling chamber sucks in the air at a velocity higher than the terminal velocity of the product. The high speed air makes the product to flow in the air stream to discharge point.

The design of the pneumatic conveyor was based on the aerodynamic properties of the material-velocity, determined by blowing the material with domestic fan and determining the distance moved per unit time.

The moving air has to overcome some resistance before it will be able to lift the material. This resistance was obtained by Eq. (20):

$$f_D = 1/2C_DA_p\rho_fV2 \qquad (20)$$

(Rajput, 2004)

where,
f_D = Resistance (drag force) (N)
C_D = Overall drag coefficient
A_p = Projected area normal to the motion direction (m^2)
ρ_f = Density of air (kg/m^3)
V = Relative velocity of the cassava flour (m/s)

The cassava flour is moved by the air as soon as the relative velocity becomes equal to the terminal velocity of the cassava flour. The terminal velocity was obtained by Eq. (21):

$$V_T = \left[\frac{2w(\rho_p - \rho_f)}{C_D A_p \rho_P \rho_f}\right]^{1/2} \qquad (21)$$

where,
ρ_p = Density of cassava flour (kg/m^3)
ρ_f = Air density (kg/m^3)
V_T = Terminal velocity (m/s)
W = Weight of particle (N)
A_p = Average projected area (m^3)

Theoretical throughput capacity and power requirement:

Throughput capacity: The throughput capacity is the quantity of material moved or produced per unit time. It can be volumetric or gravimetric. The volumetric throughput capacity was obtained by Eq. (22):

$$Q = VA\,\phi \qquad (22)$$

where,
V = Velocity of air (m/s)
A = Area available for flow of material (m^2)
Φ = Coefficient of filling.

Table 4: Result of milling efficiency

Test number	Amount passing sieve 100 (g)	Total test weight (g)
1	50	64
2	55	64
3	53	64

Determination of area of flow, A:

$$\text{Area of Flow, } A = \pi/4[(D2-d_1^2)+(D^2-d^2{}_2)]-n(Lt) \quad (23)$$

where,
D = Diameter of milling chamber
d_1 = Diameter of disk
d_2 = Diameter of shaft
n = Number of hammers
L = Length of hammer
t = Thickness of hammer

Determination of velocity of air: Velocity of air was obtained by Eq. (24):

$$V= \pi DNK/60 \quad (24)$$

where,
N = Rotational speed of rotor (rpm)
D = Diameter of fan (in)
K = Number of fan blade

The gravimetric throughput capacity was obtained by Eq. (25):

$$Qg = Q\rho_f \quad (25)$$

where,
ρ_f = Density of air = 1.239 kg/m^3

Power requirement: The power requirement of the modified cassava milling machine was obtained by Eq. (26):

$$P = Qg\ Hf \quad (26)$$

where,
H = Height of lift
f = Power factor

Efficiency test of the modified cassava milling machine: With the cassava milling machine operated at a power of 3.7 kW and a rotor speed of 1080 rpm, 1000 g of dried cassava chips were milled for 30 min. The milled cassava flour was collected in a porous sack. 128 g of the cassava flour was poured into a sieve of No. 100 and was vibrated with a mechanical shaker for 10 min. The amount of cassava flour that passed through the No. 100 sieve was weighed using a semi-automatic weighing balance. The test was repeated using the same mass of cassava flour and operating the machine at the same speed (1080 rpm) and power 3.7 kw. The result is tabulated in Table 4. Figure 4, 5 and 6 are views of the modified milling machine.

RESULTS AND DISCUSSION

Modulus of fineness and uniformity index: The result of the fineness test carried out on the milled cassava flour by the modified cassava milling machine is shown in Table 5.

Total weight of sample = 128 g
Time of vibration = 10 min

$$\%\text{Retained in Sieve} = (\text{Weight of Sample/Total Weight}) \times 100 \quad (27)$$

From Table 6,
Fineness modulus, FM = 31.25/100 = 0.31
Modulus of uniformity is 0:1:9 (coarse: medium: fine)

Efficiency of modified cassava milling machine: The result of the efficiency test is as shown in Table 4.

The milling efficiency of the modified cassava flour mill is given by Eq. (28):

$$E_m = (\text{Amount passing sieve 100})/\text{total weight of sample} \times 100 \quad (28)$$

From Table 4, the milling efficiency was calculated for three tests as shown in Table 7:

$$\text{Average milling efficiency} = (E_{m1}+ E_{m2} +E_{m3})/3 \quad (29)$$

Thus,
Average milling efficiency = (78.13 + 85.94 + 82.81)/3 = 82.3%

Grain-size distribution: From the fineness test in Table 5. Table 8 was developed.

From a grain size distribution curve, the following grain parameters were obtained:

Effective size of grain, D_{10} = 0.075 mm
D_{30} = 0.085 mm
D_{60} = 0.125 mm

Table 5: Result of fineness test on milled cassava flour

No of sieve	Weight of empty sieve (g)	Weight of sieve + sample (g)	Weight of sample (g)	Assigned number
4	492	492	0	5
10	414	414	0	4
30	379	379	0	3
50	325	337	12	2
100	310	326	16	1
Pan	372	427	100	0

Table 6: Modulus of fineness and modulus of uniformity

No. of sieve	% retained	Assigned number	Product	Sum of % retained ÷10	Nearest whole number
4	0.000	5	0.00	0	0
10	0.000	4	0.00		
30	0.000	3	0.00	0.9375	1
50	9.375	2	18.75		
100	12.500	1	12.50	9.0625	9
Pan	78.125	0	0.00		
	100		31.25		

Arora (2005) developed equations for uniformity coefficient C_U and coefficient of Curvature C_C given in Eq. (30) and (31):

$$CU = D_{60}/D_{10} \tag{30}$$

$$CC = (D_{30})^2/D_{10}D_{60} \tag{31}$$

Table 7: Average milling efficiency

Test number	Milling efficiency, $E_{m\,(\%)}$
1	78.13
2	85.94
3	82.81

Table 8: Grain size distribution of milled dried cassava chips

No of sieve	% retained	Cumulative % retained	% finer
4	0.00	0.00	100
10	0.00	0.00	100
30	0.00	0.000	100
50	9.375	9.375	90.6
100	21.875	21.875	78.1
Pan	78.125	100.00	0

Thus, substituting for the above parameters, C_U and C_C were obtained as:

$$C_U = 0.125/0.075 = 1.7$$

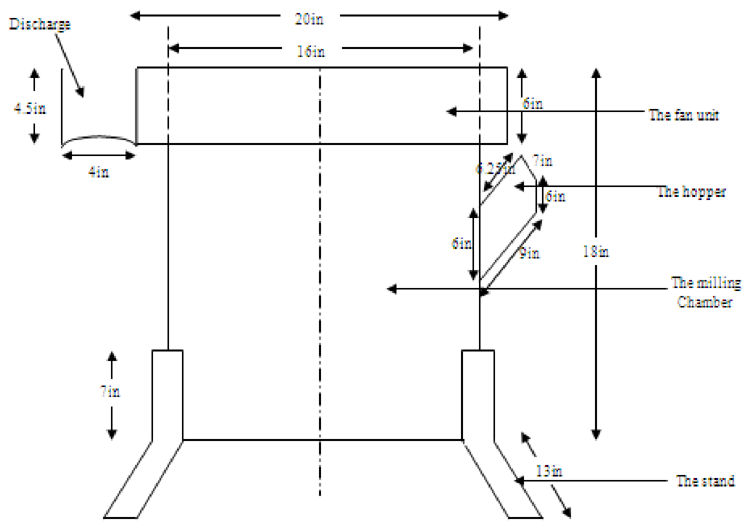

Fig. 4: A view of the frame of the modified cassava milling machine

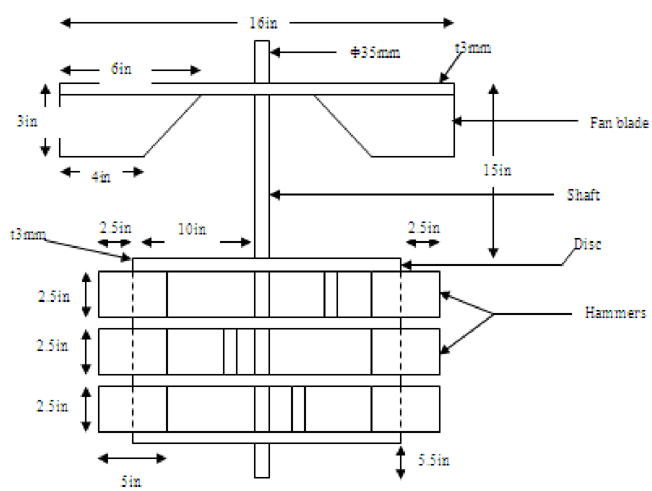

Fig. 5: Front view of the modified cassava milling machine's rotor

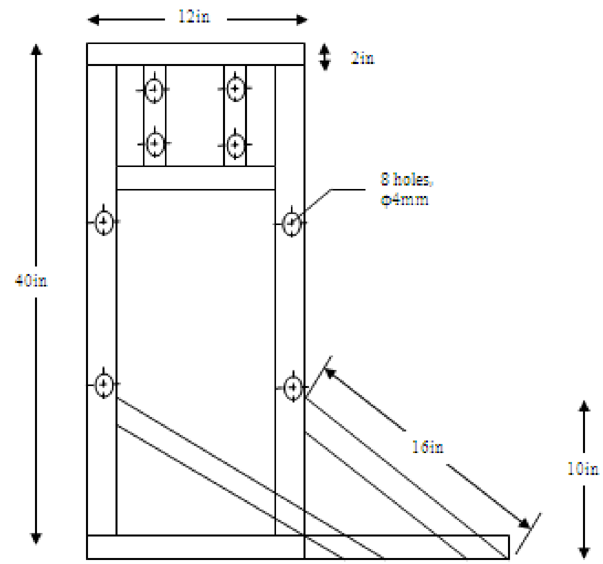

Fig. 6: The detachable motor stand of the modified cassava milling machine

$C_C = 0.085^2/0.075x0.125 = 0.28$

Grain size properties of existing mill (hammer mill): From the fineness test carried on a hammer mill in Agricultural Engineering workshop, FUTO, the following data were obtained for the hammer mill:
Fineness modulus, fm = 2.32 Uniformity Index U.I = 4:1:5
Effective size of flour, D_{10} = 0.085 mm

DISCUSSION

With the modified cassava flour mill operated by an electric motor of 3.7 KW and a rotor speed of 1080 rpm,a milling efficiency of 82.3% was obtained. During the test, it was discovered that the modified cassava flour mill requires continuous feeding of dried cassava chips. The machine was found to be dust free and the beaters do not wear when running freely.

From the fineness test, carried on the cassava flour produced by the modified cassava milling machine, the fineness modulus was obtained as 0.31 and the uniformity index as 0: 1: 9 (coarse: medium: fine). A fineness modulus of 2.10 and below signifies fine flour (Carl and Denny, 1978).

From the uniformity modulus obtained, it implies that the produced flour contains more of fine material.

Furthermore, from the grain-size distribution curve, the effective size of the flour was obtained as 0.075 mm, the uniformity coefficient, C_U = 1.7 and the coefficient of curvature, C_C as 0.28, uniformity coefficient of 1.7 as indicated by Arora (2005), signifies that the flour is uniform.

CONCLUSION

The modified cassava milling machine was designed, fabricated, tested and found to have a milling efficiency of 82.3%. Also, the fineness modulus of the flour produced was found to be 0.31 with uniformity index of 0: 1: 9 (coarse: medium: fine). Thus, the modified cassava flour mill when operated within the designed parameters will produce flour of fineness 0.31 and effective size of 0.075 mm, which is better than that of the existing mill (hammer mill) with fineness modulus of 2.32 and effective size of 0.085 mm.

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