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Cocoa Pulverising Machine Design, Calculations and Analysis

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Abstract

This paper details the design of a machine used to pulverize cocoa beans which has already been processed into cocoa bean cakes after fermentation, drying, winnowing and roasting must have been done. The machine reduces the cocoa to fine particles by discharging the cocoa press cake manually into the hopper. It goes down by gravity and is crushed by rotating blades in a rotating chamber, driven by a shaft mounted on a pulley and belt system, driven by an electric motor. The blades continue to grind until the cocoa is able to discharge itself downwards through a mesh. Mesh sizes of 0.044mm to 0.1255mm standard mesh size are used, hence the pulverized cocoa particles are of 0.044mm to 0.125mm in size. Adequate calculations are made to determine the power requirements the motor and other design parameters required.

Keywords

Pulveriser, Cocoa, Machine

1. Introduction

Cocoa bean, also called cacao bean or simply cocoa or cacao, is the dried and fully fermented fatty seed of Theobroma Cacao (cocoa was renamed Theobroma Cacao which means ‘food of the gods’ in greek, by Swedish botanist, Carlous Linnaeus in the 18th century)from which cocoa solids and cocoa butter can be extracted. Chocolate is produced from cocoa.

The cocoa tree bears two harvests of cocoa pods per year. The pods are about 20cm in length and 500gms in weight. The pods ripen to a rich golden- orange colour. Within each pod, there are 20-40 cocoa beans of about 2 cm long and covered in a sweet white pulp. (Cadbury, 2017 © Mondelez Australia Pty Ltd 2017)

The cocoa beans undergo various processes before its ready for grinding. These processes include;

1. Fermentation:- During fermentation, the cocoa pulp clinging to the beans matures and turns into a liquid, which drains away and the true chocolate flavor starts to develop
2. Drying and bagging: - when fermentation is complete, the wet mass is dried using drying equipment or traditionally by being spread in the sun. The cured beans are packed into sacks for transportation.
3. Winnowing: - The dried cocoa beans are cracked and a stream of air separates the shell from the nib, the small pieces used to make chocolate.
4. Roasting: - The nibs are roasted in special ovens at temperatures between 105 to 120 degrees Celsius. The actual roasting time depends on whether the end use is for cocoa or for chocolate. During roasting, the cocoa nibs darken to a rich, brown colour and acquire their characteristic chocolate flavor and aroma. This flavor however actually starts to develop during fermentation.
5. Grinding: - The roasted nibs are ground in stone mills until the friction and heat of the milling reduces them to a thick chocolate coloured liquid, known as “mass”. It

contains 53-58% cocoa butter and solidifies on cooling. This is the basis of all chocolate and cocoa products.

6. Pressing: - The cocoa mass is pressed in powerful machines to extract the cocoa butter, vital to making chocolate. The solid blocks of compressed cocoa remaining after extraction (press cake) are pulverized into a fine powder to produce a high-grade cocoa powder (Mondelez Australia Pty Ltd 2017).

Pulverize means to "Reduce to fine particles" (English Oxford Dictionaries 2016). It follows therefore that a pulverizer or pulverizing machine is a machine that is capable of reducing substances to fine particles (powdery form in the case of cocoa beans).

A pulverizer or machine is a mechanical device for the grinding of many different types of materials.

In engineering, Pulverization is defined as the fine crushing of a solid material (to particles of less than 5 mm) (Great Soviet Encyclopedia, 1979). Pulverization is used extensively for the concentration of mineral products in mining, as well as in metallurgy, the chemical industry, and construction.

Pulverizer machines are used to smash materials into tiny shards or granules; they can crush all types of items, including plastic, glass, aluminum, concrete, coal, rock, resin, tires, and medical waste depending on the power output. Pulverizer machines come in a number of different forms. Hammer mills, ring mills, double roll crushers, granulators, impactors, and shredders are all forms of pulverizer machines. Naroto, 1982 says that Pulverizer is used in plastic industry for plastics pulverizing including PVC recycling, rotational molding, compounding and master batching. Grinding mills are considered to be pulverizer machines because they use one, two or all three of the basic principles of particle size reduction which are; impact, attrition and crushing. With respect to speed, pulveriser machines may be classified as low speed, medium speed and high speed.

The history of pulverization dates back as early as 1824 and was envisioned by Carnot in a coal fired engine. In 1890 Diesel made use of pulverized coal in his diesel engine. Pulverized coal firing was first developed in the cement industry and then migrated to the power and process industries. Actually Thomas Alva Edison and the Niepce brothers of France were pioneers in pulverized coal firing. This technology gained momentum after World War I in the power generating industry. It was John Anderson, chief engineer of power plants at the Wisconsin Electric Power Company who introduced pulverized coal firing in power stations. (V. T. Sathyanathan, Lamar Stonecypher, 2011).

Cocoa pulverizing machines available today include, the Double Acting Pin Mill, produced by the company, Bauermeister. The Bauermeister counter-rotating mill UMP4.4N Ex pulverizes the cocoa press cake by crushing it between two pinned discs rotating in opposite directions (culled from http://www.bauermeisterusa.com).

The Duyvis cake pulverizing plant does its cake pulverizing on a large industrial scale, the cake kibbles are collected and transported to the pulverizing plant via a metal detector and ground in a classifier mill, into powder.

It is worthy of note here, that, most cocoa pulverisers or grinders available today, make use of rotating discs, rotating in opposite directions and the cocoa press cake crushed in between.

In this design however, we make use of beaters or blades, such as is used in blenders, mini home grinders, yam pounders, as we strongly believe we can achieve our aim of reducing cocoa to fine particles in this way.

2. Types of Pulverisers

1. Low Speed mills e.g. ball tube mills
2. Medium Speed mills e.g. bowl, ball and race, roller mills
3. High Speed Impact Mills. The high speed mills are used mainly for lignite.

Ball Tube Mill

Ball tube mills are either pressurized or suction type. In the pressurized type, the hot primary air is used for drying the coal and to transport the milled coal to the furnace. In this type, leakage in the mill area is high.

In the suction type, the exhauster is used for lifting the milled coal from the pulverizer to the furnace through a cyclone. The tube mills have a large circular drum, with adequate ball charge, which is rotated at about 70% of the speed at which the ball charge would be held against the inner surface by centrifugal force. In this mill the grinding balls can be replenished on the line.

Normally the ball mill designers use three types of balls with three different diameters. These balls reduce in size as the mills operate and so the highest size ball is normally used for recharging. In earlier days, most of the ball mills had a single inlet and outlet, but now designers use both ends to feed coal and also for taking out pulverized coal. The control systems are well made to understand the requirement of ball charge and the output from the mill. Ball mills are always preferred to be operated at full capacity because the power consumption of this type of mill is very high at lower loads when compared with other types. Ball mills can be designed for a very high capacity like 75 tons per hour output for a specific coal.

Vertical Spindle Mill

There are many different varieties of vertical mills. Designers use large steel balls ranging from 2 to 6 or more between two grinding rings for pulverizing. There are also other types like conical rollers with shallow bowl; deep bowl, etc. where load is applied on the rollers and the bowl rotates while pulverizing. These types of mill are designed normally up to 60 tons per hour for a specific coal; however there are vertical mills with 90 tons per hour output. A vertical spindle mill is also designed for pressurized and suction type requirements.

High Speed Impact Mill

This type of mill uses a central horizontal shaft which has a number of arms, and a beater of different design is attached to these arms to beat the coal to be pulverized. High speed impact mills are mainly used in pulverizing lignite.

3. Significance of Study

Cocoa beans is one of the leading export commodities in Nigeria and rising international market prices for cocoa have continued to encourage Nigerian farmers to rehabilitate abandoned farms and also increase area under protection.

There are 14 cocoa producing states in Nigeria and a total planted area of 640,000 hectares. Annual production has fluctuated between 250,000 and 320,000 tons over the past five years.

About 85 percent of total cocoa production is exported as cocoa beans while the remaining 15 percent is processed locally into butter, liquor, powder and cake before being mostly exported. However, a lot of cocoa based products are imported into the country. This means we lose foreign exchange. Nigeria could spend less on importation of cocoa based produce if we could make good use of our cocoa beans by being able to pulverize and turn to secondary and tertiary produce. Such secondary and tertiary produce include cocoa cake, cocoa butter, cocoa powder, etc.

4. Design Concept

The concept consists of a grinding or milling chamber, a rotating shaft on which is mounted beaters on a number of arms. The beaters have a knife edge and rotate about the shaft in the grinding chamber. This reduces the cocoa to fine particles. The already reduced particles are discharged from the bottom of the grinding chamber.

5. Machine Components

These are the units of the machine assembled together to form the whole and complete machine. These include: The machine structural frame with its attached, grinding blade (beater), pulleys, shaft, electric motor which was selected.

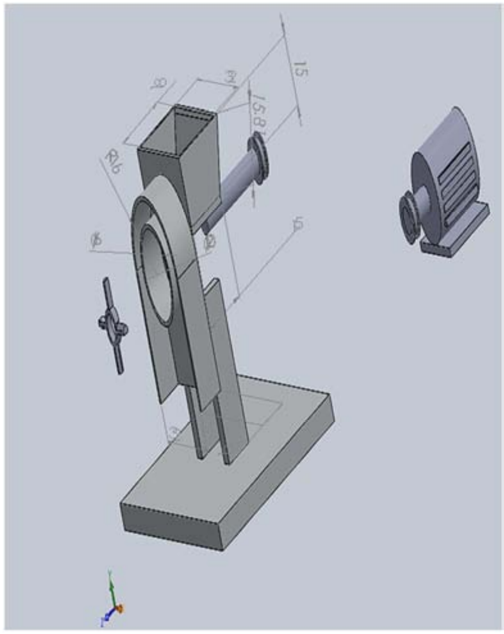

Figure 1. *Exploded view of components. From left to right (blade, grinding chamber and hopper, shaft and pulley, motor and pulley).*

6. Material Selection

Material selection to meet the functional requirements and standard of the various machine components is very important, as there are varieties of materials available to choose from and new materials are being developed with unique properties and applications.

Table 1. *Component Parts and Materials Selected.*

COMPONENT	FUNCTION	MATERIAL SELECTED	REASON FOR THE SELECTED MATERIAL
1. Structural frame	Serves as the body of the machine and shows the shape of the machine	Carbon Steel	Rigidity and strength
2. Grinding blade(beater)	Grinding into smaller particles	Mild Steel	Strength and it's cheap
3. Bearing	Permits relative motion between the motor and the grinding shaft	-	-
4. Pulley	Transfers rotational motion from motor-end to the shaft-end	-	-
5. Mesh	Serves as a sieve to collect the fine particle from the grinding chamber	Aluminum	Corrosion resistant and cheap
6. Shaft	It transmits motion from to the pulley and belt drive system	Steel	Hardness and rigidity
7. Electric Motor	Generates the power that drives the grinding process	-	-

7. Design Factor

These are features that affect or influence the design of the machine and perhaps some of its components. However, only the main factors will be considered and other minor factor will have no effect in the design. These factors are:

i. Strength of the material used: - because of the vibration from the machine, it is important that the materials be of good strength.
ii. Resistance to corrosion: - various forms of steel are used for the corrosion resistance properties. So it allows the machine operate even in moist or damp conditions without been corroded.
iii. Ease of maintenance: - The machine is made in a way that will be easy to maintain. This is because components for various functional requirements are independent of other functional requirements. For example, the blade is separate from other parts and can be easily replaced if it goes bad or if need be.

7.1. Design Analysis of the Machine Components

The density of cocoa press cake is $35\, lb/ft^3$ and $560.7\, kg/m^3$ (Anval Valves Pvt Ltd Bulk density chart, 2013), the value was also used in Brabender Technlogie's, 'Ingredient Bulk Density table'. This value was adopted and used in this project.

1. Grinding Chamber:

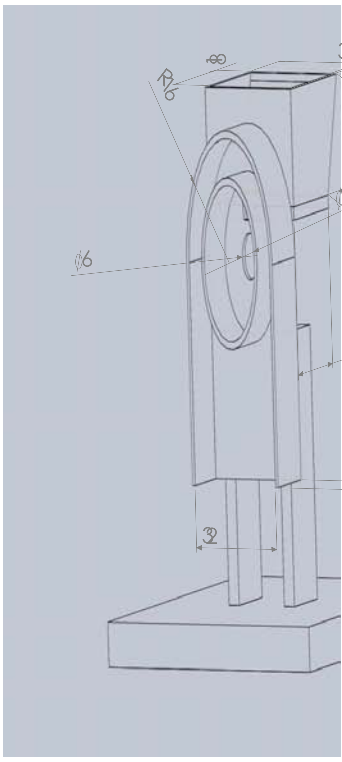

Figure 2. *Grinding chamber and Hopper with dimensions (scale: 1mm to 10units).*

The grinding is done in the inner cylindrical chamber which is 20mm in diameter and 10mm in height.

$$volume\ of\ grinding\ chamber = \pi r^2 h = \pi \times 100^2 \times 100 = 3141593mm^3$$

2. Blade:

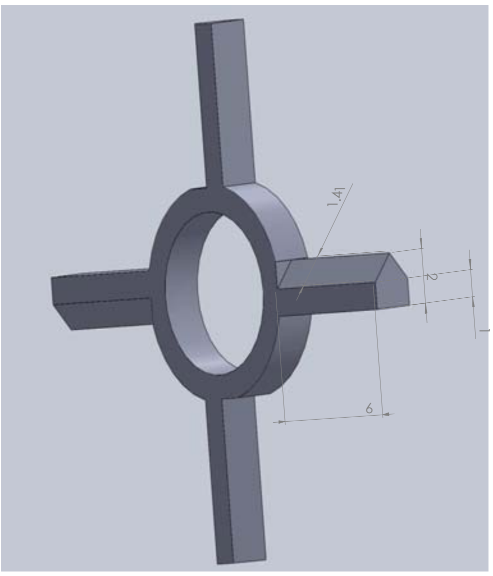

Figure 3. *Blade or Beater with four arms (scale: 1mm = 100units).*

Design parameters of the beater:

$$Area\ of\ cutting\ face\ of\ blade = 141mm \times 600mm = 84600mm^2$$

$$each\ arm\ of\ the\ blade\ has\ 2\ faces \Rightarrow area = 8460mm^2 \times 2 = 16920mm^2$$

$$height\ of\ blade = 200mm$$

$$volume\ of\ blade = 16920mm^2 \times 200mm = 3384000mm^3$$

3. Electric Motor: 2hp motor with Torque of 450rpm

7.2. Determination of the Crushing Force and Power Requirement

The grinding or crushing force is required to grind the cocoa press cake into fine powder. Crushing Force;

i. Force = Pressure * Area

ii. Weight = Mass × Acceleration due to gravity

The weight of the cocoa press cake is given by;

Mass of press cake × Acceleration due to gravity

The force required to crush the cocoa press cake = pressure × area

For good efficiency of the machine, the force to be applied by the cutting or crushing device should not exceed the weight of the cocoa press cake.

Hence,

Weight of Press Cake ≥ Pressure × Area

Let Weight of Press Cake = Cutting Pressure × Area of Blade in contact with press cake

$$mg = Pressure \times Area$$

$$m \times g \times h = pressure \times Area\ of\ blade \times height\ of\ blade$$

$$m \times g \times h = pressure \times volume\ of\ solid\ blade$$

$$\frac{m \times g \times h}{Volume} = pressure$$

Let the crushing pressure be denoted by P_c.

Crushing pressure for the press cake;

Therefore;

$$P_c = \rho_c \times g \times h \quad (1)$$

Where:

$$\rho_c = Density\ of\ cocoa\ press\ cake = 560.7\ kg/m^3$$

$$g = accelelration\ due\ to\ gravity = 9.81\ m/s^2$$

$$h = height\ of\ the\ beater = 0.2\ m$$

Pressure, $P_c = 560.7 \times 9.81 \times 0.2m$

$$P_c = 1100\ N/m^2$$

Then the force acting on the edge of the beater in contact with the cocoa press cake is given by

$$N = P_c \times A \quad (2)$$

Where;
N = Force acting on the surface area of the beater in contact with the cocoa press cake
A = Area of edge of the beater in contact with the cocoa press cake=0.1692 m^2

$$N = 110 \times 0.1692$$

$$N = 186.12\ N$$

The turning effect of beater;

$$Torque\ T = Force \times Perpendicular\ Distance \quad (3)$$

$$T = N \times distance\ of\ beater\ from\ center\ of\ pivot$$

$$d = distance\ of\ beater\ from\ centre\ of\ pivot = 0.5m$$

$$T = N \times d$$

$$= 186.12 \times 0.5m$$

$$T = 93.06\ Nm$$

Then the power requirement to operate the machine,

$$P = Torque(T) \times angular\ speed(\omega) \quad (4)$$

$$P = T \times \omega$$

Where;

$$\omega = 2\pi N/60 \quad (5)$$

Speed of electric motor is 450 rpm
Take factor of safety as 3.0 for the reliability purpose.
This implies that;

$$= \frac{2 \times \pi \times 450 \times 93.06}{60}$$

$$P = 4385.35 watt$$

Considering the chosen factor of safety 3 therefore,

$$P = 3 \times 4385.35$$

$$P = 1316\ watts$$

Recall that,

$$1\ horsepower = 746\ watts$$

$$x horsepower = 1316\ watts$$

$$746x = 1316$$

$$x = \left(\frac{1316}{746}\right) hp$$

$$x = 1.764 hp$$

Then an electric motor of 2hp with speed 450 rpm was chosen.

7.3. Belt Design

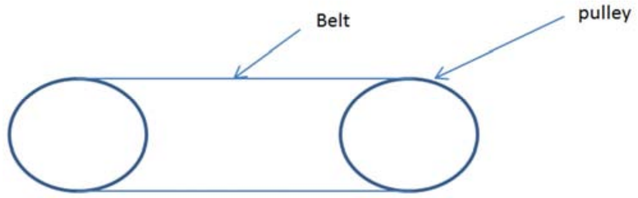

Figure 4. *Pulley and Belt Schematic.*

The center to center distance of both pulleys is determined by the formula

$$x = \max\left(\frac{3D}{2} + \frac{d}{2}\right) \text{ (Gupta J. K and Khurmi R.S, 2004) } (6)$$

Where D and d = diameter of large and small pulleys

$$x = max\left(\frac{3 \times 230}{2} + \frac{80}{2}\right)$$

$$= \max(345 + 40)$$

$$x = 385mm$$

We shall however use a round figure of $x = 400mm$.
Length L, of belt for open belt driven is given by

$$L = \pi\left(\frac{D+d}{2}\right) + 2x + \left(\frac{D+d}{2}\right)^2 \quad (7)$$

$$= \frac{\pi(0.23 \times 0.08) + 2(0.4) + (0.23 + 0.08)^2}{4(0.4)}$$

$$= 0.596m\ or\ 596mm$$

We use this as a guide to select belt for the pulley.

7.4. Maximum Power Transmitted by Belt

$$P = (T_1 - T_2)v \quad (8)$$

P= Power of electric motor = 1492 Watts or 2hp

$$T_1 = Tension\ on\ tight\ side$$

$$T_2 = Tension\ on\ slack\ side$$

$$v = Belt\ speed\ in\ m/s$$

$$Belt\ Speed\ v = \pi Dn$$

$$v = \pi \times 0.3 \times \frac{450}{60}$$

$$v = 7.07\ m/s$$

$$P = (T_1 - T_2)v$$

$$1492 = (T_1 - T_2)7.07$$

$$T_1 = T_2 + \frac{1492}{7.07}$$

$$T_1 = T_2 + 211.033 \quad (9)$$

Also; $T_1 = 3.15T_2 - 6.770$ (Oweziem et al, 2015) (10)

Equation (9) – Equation (10)

$$\rightarrow T_1 - T_1 = T_2 - 3.15T_2 + 211.033 + 6.770$$

$$0 = -2.15T_2 + 217.802$$

$$\Rightarrow 2.15T_2 = 217.802$$

$$T_2 = \frac{217.802}{2.15} = 101.304N$$

$$T_1 = 3.15(T_2) - 6.770$$

$$= 3.15(101.304) - 6.770$$

$$\Rightarrow T_1 = 312.336N$$

7.5. Shaft Design

In the shaft design, the minimum shaft design that can withstand the load shaft will be subjected to (bending load, torsional load, axial pulley weight) is given by;

$$d = \sqrt[3]{\left(\frac{16}{\pi S_y}\left(\sqrt{((M_b \times K_b)^2 + (M_t \times K_t)^2)}\right)\right)} \quad (11)$$

Where;

$d = maximum\ diameter\ of\ the\ shaft$

$M = Maximum\ bending\ stress$

$M_x = Maximum\ bending\ stress$

$K = Fatigue\ factor\ for\ bending\ moment$

$K_x = Fatigue\ factor\ for\ torsional\ moment$

But for Torsional moment torqueM_t,

$$M_t = (T_a - T_b)R_b \quad (12)$$

Where

$T_a = belt\ tension\ tight\ side = 312.336N$

$T_b = belt\ tension\ slack\ side = 101.304N$

$R_b = radius\ of\ beater\ pulley = 115mm = 0.115m$

Then,

$$M_t = (312.336 - 101.304)0.115$$

$$= 24.269Nm$$

$$= 24.269 \times 10^3 Nmm$$

7.6. Machine Pulverising Capacity

The maximum pulverizing capacity is determined as follows;

Maximum volume of cocoa pulverized $V_{cp} = V_h - V_b$ (13)

Where;

$V_{cp} = Maximum\ pulverizing\ capacity$

V_h=*Volume of cylinder enclosing beater and cocoa to be pulverised=3.14×10-3 m*^{3}

$V_b = Volume\ occupied\ by\ beater = 6.9105 \times 10^{-6} m^3$

Therefore, $V_{cp} = (3.14 \times 10^{-3} - 6.9105 \times 10^{-6}) = 3.135 \times 10^{-3} m^3$

8. Result and Discussion

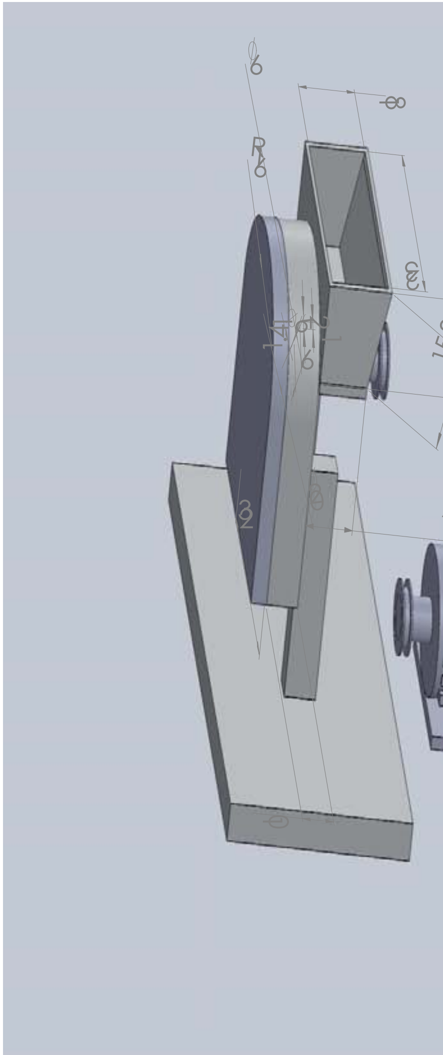

Figure 5. *Assembled Pulveriser.*

The machine testing was carried out; the cocoa press cake fed to the machine through the hopper was grinded, with the machine components working according to specification and standard to produce a fine powder through the outlet.

It was found that resistance and the overall performance of the electric motor were satisfactory.

9. Conclusion

Having concluded design of the machine, we state here that the need for having pulverized cocoa which is important for personal and industrial use is satisfied with an alternative and less common approach to pulverizing cocoa, which is the use of beaters as against the use of discs, usually counter-rotating as the grinding tool.

Relatively low cost materials used for the fabrication of the machine and the longevity of each of these materials in service makes it affordable for domestic and industrial use.

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