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Design, Fabrication and Performance Evaluation of a Refiner Mechanical Pulping Machine

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ABSTRACT*: This study was conducted to enhance the local production of mechanical pulp especially in southwestern Nigeria, which has a higher yield and lower environmental pollution effects compared with chemical pulping. The fabricated machine consists of the hopper; discs that are housed in a chamber, and a belt, shaft and pulley configuration that transmits the power generated by an electric motor or gasoline engine. Refining is achieved by two discs, one stationary and the other rotating, rubbing against each other at predetermined and regulated clearances to produce the grinding effect. The refining disc employed for the pulper is made of stainless steel material with bar width of 2.5mm and groove depth of 2-3mm. Other parts added are the water feed and its support and a sieve and its holder. The performance evaluation of the machine followed TAPPI 2007 standards and chips from Bambusa vulgaris and Gmelina arborea were pulped yielding 93.3% and 97.8% respectively. The refined pulp was analysed for fibre characteristics and comparisons were made between pre-treated and untreated pulps.*

KEYWORDS: *Pulping, Refining, Fibre characteristics*

I. INTRODUCTION

Pulping is basically the liberation of fibres from wood so that they can be reformed into paper sheets [1]. The pulping process is achieved either through chemical, mechanical or a combination of both means with each having its merits and demerits. A mechanical disc pulper is the equipment used to achieve mechanical disintegration of wood into its fibrous components using refining discs. Although the most widely used means of defibrillation is the chemical means, however, concerns have been raised by environmentalists as well as conservationists about the effects that the effluents generated by the pulping chemicals have on the environment. Chemical pulping process is characterized by high raw material consumption, capital and energy cost, environmental pollution amongst others [1]. These have necessitated looking into mechanical pulping as the alternative means of pulping or complementary to chemical pulping. Mechanical pulping is achieved either through the ground-wood process or the disc refiners. The preference for disc refiner is due to its proven ability to be modified to suit different pulping purposes such as in composite applications as well as better preservation of the wood fibres. In the growing sector of an industry, the origins of the timber used in tissues, serviette and toilet papers, etc are called into question. Although it is established that mechanical pulps are lower in strength due to increased number of bruised and crushed fibres during the process however, the pulps can also be used for purposes afore mentioned where strength of the pulp is not of utmost importance. The study also aims to decentralize the integrated pulp mills as the production of pulp from wood would be carried out on cottage levels while also ascertaining the suitability or otherwise of mechanical pulping for our indigenous non-woody fibre sources.

II. MATERIALS AND METHODS

Disc refiners consist of a hopper that feeds wood chips into the disc chamber housing the refining discs through a conveyor and is powered by an electric motor or gasoline engine through the pulley, belt and shaft configuration. The methodology is that of twin discs, one stationary and the other rotating, rubbing against each other at predetermined and regulated clearances to achieve refining. For easy categorization, the machine is divided into the main part and the auxiliary parts. The main part consists of: the hopper, the discs and disc chamber, the conveyor, shaft and pulleys; while the auxiliary parts are: the support, water support and channel, the sieve and collector and the power drive. Refining disc Stainless steel was selected as a material for use in the construction of the refiner disc. Stainless steels contain chromium, nickel, and other alloying elements that keep them bright and rust resistant in spite of moisture or the action of corrosive acids and gases. They are also very hard; some have unusual strength and will retain that strength for long periods at extremely high and low temperatures, which makes them suitable for when heat is applied as pre-treatment. These characteristics make it suitable for use to prevent corrosion and increase the wearing resistance of the bars and grooves on the refiner discs.

From the materials properties of steel, stainless steel has allowable stress σ allowable = 250MPa with ultimate stress of 360MPa and density of 8.19g/cm3. The discs have a diameter of 140mm, with bar width of 2.5mm and groove depth of 2-3mm.

2.1. Disc chamber and gap regulator

The diameter of the disc chamber was 220mm, since it houses a disc of radius 70mm, leaving a clearance of 40mm on both sides. To determine the thickness of the material for the chamber, the chamber was considered as a thin walled cylinder bearing fluid under atmospheric pressure. From the properties of steel, the allowable stress σ_{yield} = 250MPa (Howard and Timothy, 1985).
The yield strength of thin walled cylinder bearing fluid under atmospheric pressure is given as:

$$\sigma_{yield} = \frac{Pr}{t} \qquad \text{(Beer and Johnston, 1992)} \quad - \quad - \quad - \text{(I)}$$

Where,

$r = radius, t = thickness, P = atmospheric\ pressure\ (\ell gh)$

$$\therefore\ t = \frac{Pr}{\sigma_{yield}}$$

Taking a factor of safety of 4,

$$\sigma_{allowable} = \frac{520MPa}{4} = 130MPa \equiv 1.3 \times 10^8 N/m^2$$

Given that,

$r = 110mm, \quad \sigma_{yield} = 1.3 \times 10^8 N/m^2, \quad P = \ell g h$

$$Taking \quad \ell = \frac{1000kg}{m^3}, \quad g = \frac{9.81m}{s^2}, \quad h = 70mm,$$

$$P = 1000 \times 9.81 \times 0.07 = 686.7N/m^2$$

Therefore,

$$t = \frac{686.7 \times 110}{1.3 \times 10^8} = 5.81 \times 10^{-4} m \equiv 0.5mm$$

2.2. The hopper

The hopper is the part of the machine serving as inlet for the wood chips and water into grinding chamber. The stainless steel is adopted for the hopper to avoid corrosion due to constant exposure to moisture. The hopper is of the shape of a frustum of a pyramid. The volume is determined as follows:

$$Volume\ is\ given\ by\ V = \frac{AH}{3} \quad - \quad - \quad - \quad (II)$$

Where V is volume, A is area of base of pyramid, and H is height of pyramid.

Using similar triangle theorem, height:

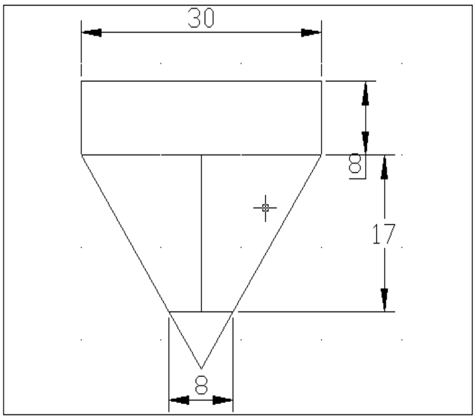

Figure 1: Front view of the hopper

$$From\ figure\ 1, \quad \frac{h}{8} = \frac{H}{30}, \text{where } H = h + 17$$

$$therefore, \frac{h}{8} = \frac{(h+17)}{30}, 30h = 8(h+17), h = 6.18cm$$

Total volume of pyramid Vp: $Vp = (1/3)(30)^2 \times (6.18 + 17) = 6954cm3$
Volume of truncated pyramid: $Vs = (1/3)Ah = (1/3) \times 8 \times 8 \times 6.18 = 131.84\ cm3$
Volume of top cuboid: $Vt = d^2 \times h, \quad d = 30cm, \quad h = 8cm$
therefore, $Vt = 7200cm^3$
Volume of cylinder enclosing shaft: $Vc = \pi r^2 h, \quad r = 3.5, \quad h = 16cm$
therefore, $Vc = 615.75cm^3$
Total volume of hopper refiner is $V = (Vp - Vs) + Vt + Vc$
then: $V = (6954 - 131.84) + 7200 + 615.75 = 14637.91$

2.3. The shaft

The shaft is a metal rod of a mild steel material. This was adopted to bear the weight of the stainless steel material designed for use as grinding discs. The length of the shaft is put at 640mm to accommodate the lengths of the gap regulator, grinding chamber, conveyor, and connection to the pulley end and edge clearances. The diameter of the shaft has to be adequate to bear the weight of the grinding discs and the pulley. Thus, it is determined as follows:

Given that,
Density of Stainless steel $= 8.19\,g/cm^3$, *and Density of Mild Steel* $= 7.86\,g/cm^3$
Expected mass of the grinding discs =

$$\rho = \frac{m}{v} \quad - \quad - \quad - \quad (III)$$

$$\rho_{Stainless\ steel} = \frac{Mass_{grinding\ disc}}{Volume_{grinding\ disc}}, \quad Mass_{grinding\ disc} = \rho_{Stainless\ steel} \times Volume_{grinding\ disc}$$

$$Volume_{grinding\ disc} = \pi r^2 h = 3.142 \times 9^2 \times 1 = 254.5cm^3$$

$$Mass_{grinding\ disc} = 8.19\,g/cm^3 \times 254.5cm^3 = 2084.35g$$

For 2 grinding discs, the total mass expected is $2 \times (2084.43)g = 4168.71g$

$$\rho_{Mild\ steel} = \frac{Mass_{expected}}{Volume_{shaft}}, \quad \emptyset_{shaft} = 2\left[\sqrt{\frac{Mass_{expected}}{\pi h\, \rho_{Mild\ steel}}}\right]$$

$$\emptyset_{shaft} = 2\left[\sqrt{\frac{4168.71}{\pi \times 64 \times 7.86}}\right] = 3.24cm$$

The diameter of the shaft is calculated as 3.24cm. However, to cater for other weights such as pulley, etc, a diameter of 5cm was used as design for the shaft.

2.4. Bearings

For the refiner pulper, due to the weight of the stainless steel disc to be supported by the machine and the high speed of torque needed for fibre disintegration, the pillow bearings are selected for use. And to ensure rigidity, due to the machine configuration design, two bearings are needed, one to regulate the motion from the pulleys and the other for the conveyor and refiner discs.

The pulley

To determine the size of the pulley;

$$\frac{N_E}{N_M} = \frac{D_M}{D_E} \quad (Childs, 1998) \quad - \quad - \quad - \quad (IV)$$

Where,
N_E = *Speed of the electric motor* = 3600*rpm*
N_M = *Desired speed of the pulper* = 1400*rpm*
D_E = *Diameter of the motor pulley* = 5.5*cm*
D_M = *Diameter of the pulper pulley* = ?

$$D_M = \frac{N_E \times D_E}{N_M} = \frac{3600 \times 5.5}{1440} = 13.75cm$$

Therefore, the diameter of the machine pulley is 13.75cm.
Figure 2 shows an exploded view of the designed machine parts:

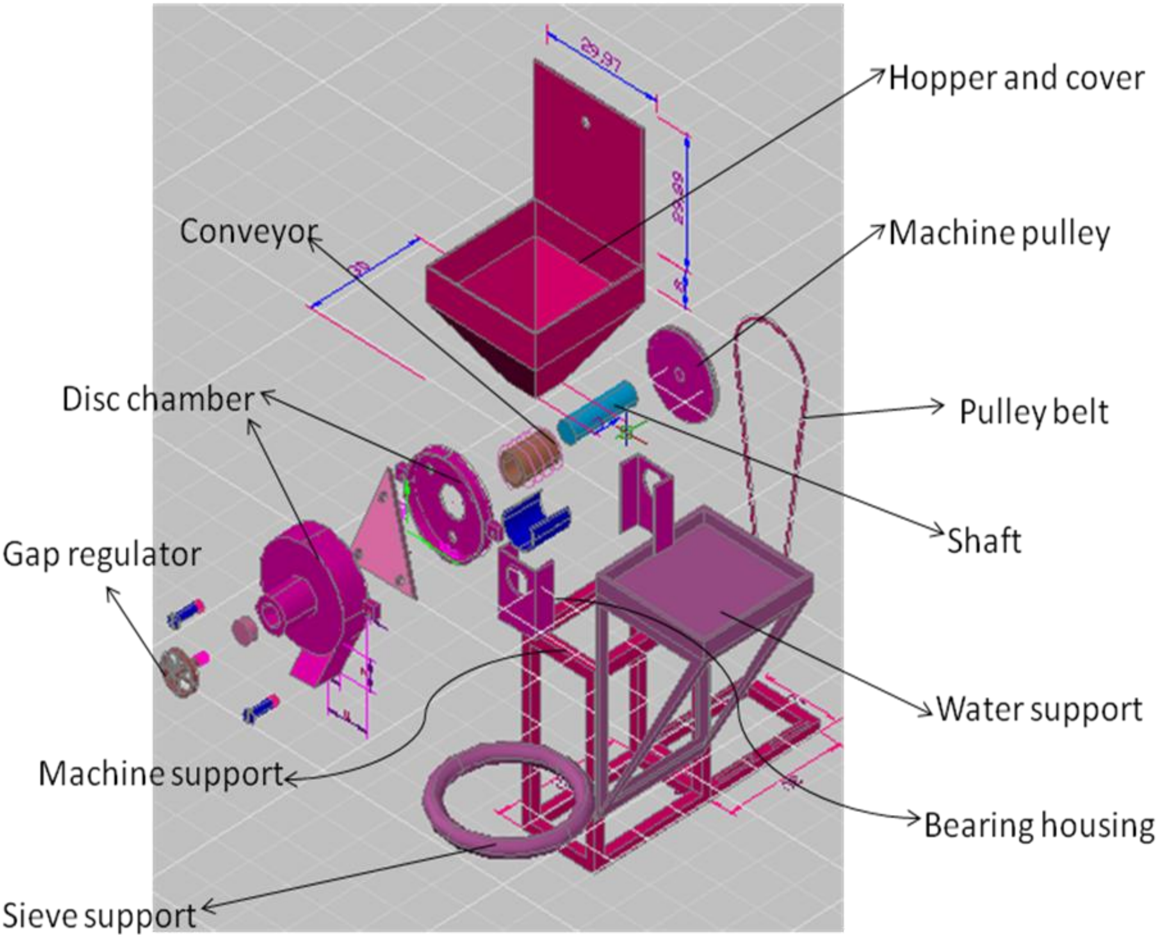

Figure 2: Exploded View of the Refiner Pulper

2.5. The test specimen

The test specimens used were the *Bambusa vulgaris* (Bamboo) stem and *Gmelina arobrea* (Gmelina). Both specimens were obtained from Iseyin, Oyo State Nigeria which is on latitude 70 57'N and longitude 30 35'E [2]. The ages of the Bamboo stem was about 24 months and the Gmelina was about 18 years. The stems were debarked and cut into were of the chip size of 25mm by 5mm by 5mm.750g of the chips were pre-treated with steam. This was done by boiling the chips continuously for three hours at a temperature of about 1000C and then left in the hot water bath until it cooled. The evaluation process was in accordance with TAPPI 2007 standards for mechanical pulping experiments.

Determining fibre-water ratio: The processing of both chips and pre-treatments were carried out differently, following the flow chart in fig 3.9. A medium consistency refining of 10% was adopted. Calculating the volume of water required for a batch of 750g fibre each,

$$C = \frac{F}{W} \times 100 \qquad (TAPPI, 2007)$$

$Where,$

$C = Consistency\ of\ pulp\ in\ percentage$

$F = Mass\ of\ fibre$

$W = Total\ mass\ of\ pulp\ slurry\ (fibre + water)$

$Therefore,$

$$W = \frac{F}{C} \times 100 \quad = \quad \frac{750}{10} \times 100 \quad = \quad 7500g$$

$Converting\ to\ volumes\ using\ the\ known\ density\ of\ water\ = 1g/cm^3$

$$\rho = \frac{M}{V}, \qquad V = \frac{M}{\rho}, \quad V = \frac{7500}{1} = 7500\,cm^3$$

$Converting\ from\ cm^3\ to\ litres, \qquad 7500\,cm^3 \equiv 7.5 litres$

III. THE REFINING AND PERFORMANCE EVALUATION

The chips were fed from the hopper to the grinding disc through the conveyor. The feed rate depended on the speed of rotation of the shaft around which the conveyor was attached, which was determined by the peed transmitted to the machine from the motor. A grinding gap of 3mm between the discs was used at the first pass, the mashed fibres were collected on the screen while the water passes through the screen and was returned to the water feed container to conserve water usage. The mashed fibres were fed again into the hopper and then to the grinding disc. The grinding gap was reduced by about 1.5mm giving about 1.5mm at the second pass.The refined pulps obtained were subjected to fibre analysis to evaluate the characteristics of the fibres obtained.

Results and Discussion

The yield obtained from the refining process was determined as follows:

$$Yield = \frac{Mass\ of\ pulp\ obtained}{Mass\ of\ Chips} \times 100$$

Yield from air dried *Bambusa vulgaris* chips (untreated)

$$Mass\ of\ chips = 750g$$

$$Mass\ of\ pulp\ obtained^{*} = 695g$$

$$\therefore Yield = \frac{695g}{750g} \times 100 = 92.6\%$$

Yield from pre-steamed *Bambusa vulgaris* chips

$$Mass\ of\ chips = 750g$$

$$Mass\ of\ pulp\ obtained^{*} = 700g$$

$$\therefore Yield = \frac{700g}{750g} \times 100 = 93.3\%$$

Yield from *Gmelina arborea*

$$Mass\ of\ chips = 1000g$$

$$Mass\ of\ pulp\ obtained^{*} = 978g$$

$$\therefore Yield = \frac{978}{1000} \times 100 = 97.8\%$$

Therefore, the average pulp yield obtained = 94.5%

$(Mass\ of\ pulp\ obtained^{*} = Mass\ of\ unscreened\ pulp\ for\ handsheet\ forming)$

The yield obtained from the pulping process was about 94.5% on the average and is within the range acceptable for mechanical pulping as the yield from refiner mechanical pulping is usually between 90-93% [3]. This is due to extractive contents in the species that may have dissolved during the processes as well as other fibre losses due to spills.

Fibre analysis of the refined pulp samples

The pulp obtained from the refining process was subjected to fibre analysis to determine the effect of the refining process on the fibre properties. Some of the pulp slurry obtained was pipette on a clean slide and viewed under a Carl Zeiss photomicrograph microscope. Other morphological indices were also derived. The results are as shown in tables 1 and 2:

Table 1: Mean Values of Fibre Analysis for the Refined Bamboo Pulp

REFINED BAMBOO	PRE-TREATED	UNTREATED
Fibre Length (mm)	1.71	1.53
Fibre Diameter (μm)	14.38	13.39
Lumen Width (μm)	9.80	9.30
Cell wall thickness (μm)	2.29	2.05
Runkel ratio	0.53	0.51
Coeff. of flexibility	67.00	70.50
Felting power	124.32	115.37

From table 1, the average fibre lengths of the pre-treated and untreated pulps are 1.71mm and 1.53mm respectively. The difference in fibre lengths between the pre-treated and untreated wood chips with the pre-treated having a longer fibre length, the claim that pre-treatments given to wood chips in forms of steaming and chemical additions enhance the quality of pulp produced by preserving the fibres have been justified. However, the average fibre lengths of pulps obtained from the process is still within an acceptable range for papermaking as the higher the fibre length, the greater the tearing resistance of the paper [4].

Table 2: Mean Values of Fibre Analysis for the Refined Gmelina Pulp

GMELINA		
	PRE-TREATED	UNTREATED
Fibre Length (mm)	1.71	1.66
Fibre Diameter (μm)	24.56	24.38
Lumen Width (μm)	14.21	13.63
Cell wall thickness (μm)	5.39	5.38
Runkel ratio	0.86	0.82
Coeff. of flexibility	58.20	56.17
Felting power	72.75	69.57

Table 2 shows a reduction from 1.71 to 1.66mm. The reasons for difference in values of the fibre lengths obtained from the pre-treated and untreated pulps of bamboo can also be advanced for the same trend that is observed in the refined gmelina pulp.

IV. CONCLUSIONS

The fabricated mechanical disc pulper has proven to be viable for the purpose of mechanical pulping as the output from the machine competed favourably with mechanically refined imported pulps in different forms of observation made: physical appearance, fibre analyses, morphological indices and microscopic evaluations, bearing in mind the variations in pre-treatments, fibre source and other manufacturing processes such as bleaching already incorporated into the imported mechanical pulps. As opposed to the foreign design of mechanical pulpers which is high in capital costs, requires the use of sophisticated machinery, equipments and materials for its fabrication repair and maintenance; the constructed refiner is of a much simpler configuration, cheaper and easy to construct, dismantle, repair and maintain using locally sourced materials and technology.

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