

## DESIGN AND FABRICATION OF A HYDRAPULPER FOR DISINTEGRATING DISUSED Tetra Pak<sup>®</sup> BEVERAGE CARTONS

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### **Abstract**

*This study is aimed at producing paper from disused Tetra Pak<sup>®</sup> beverage cartons usually found in Nigerian landfills and dumpsites, creating environmental problems. Their use will reduce the over-exploitation of trees in the forest for papermaking. A laboratory-scale hydrapulper of 80dm<sup>3</sup> was designed and fabricated using locally sourced materials to make the disintegration process cost effective. The performance of the hydrapulper was evaluated at three carton slurry consistencies: low, medium and high consistencies where 3%, 8% and 13% of carton pieces were repulped in water respectively. The fabricated hydrapulper performed satisfactorily to disintegrate and separate the paper component of the cartons from its low density polyethylene and aluminum foil components. The highest average pulp yield of 60.57% was recorded at low consistency although there is no significant difference between the pulp yields at each consistency. It can be concluded that about 80% of the paper component of the carton can be recovered for papermaking.*

**Keywords:** Hydrapulper, Tetra Pak<sup>®</sup>, beverage cartons, disintegration, consistency.

## Introduction

Global demand for paper has been on the increase over the years due to its use for diverse purposes in all works of life ranging from communications (writings, stamps, newspapers and greeting cards) and business (advertisements, money and cheques), to packaging of foods and beverages (paper crockery and cutlery, coffee filters, liquid carton board and folding box-board). The effect of producing these grades of paper from virgin pulp, together with the use of sawn timber for furniture and construction purposes can be observed in the over-exploitation of trees in forests, as Kolajo (2009) reported that half of the world's timber is needed to make paper products such as tissues, paper towels, handkerchiefs, gift-wrapping paper etc. Olorunnisola (2013) however predicts that the growing quest for pulpwood for papermaking in Nigeria will increase to about 2,719,900m<sup>3</sup> before the end of 2020.

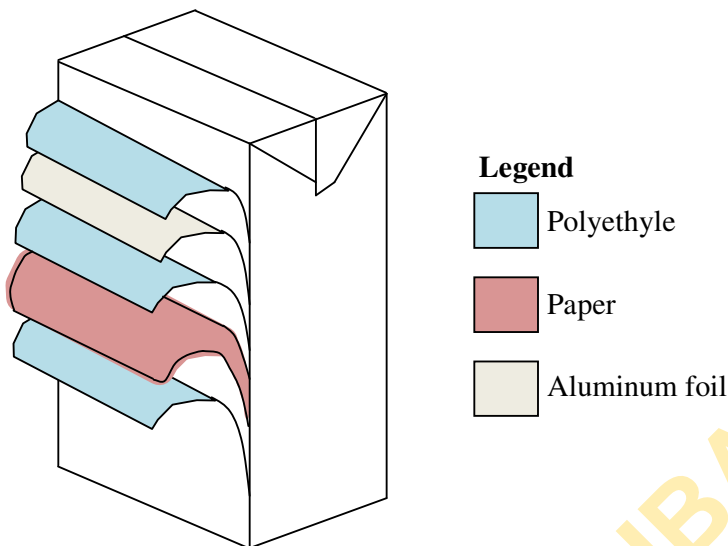
Tetra Pak<sup>®</sup> is a food processing and packaging company that produces carton-like containers that hold many foods and drink items such as dairy, juice, spirits, beans and vegetables (Stearns, 2013). These beverage cartons are made from softwood trees such as pines, spruce and birch that are known for their exceptionally long and strong fibres which give the desired rigidity required to maintain the shape of the cartons (Pablo, 2009). The cartons are usually multi-layered poly-coated paperboards that are easily re-pulpable in water because they contain no wet strength additives. The paper content represents 75% of the total weight of the package, with barriers consisting of four or five layers of low-density polyethylene of about 20% by weight and a remaining 5% thin layer of aluminum foil (Abreu, 2002) as shown in Fig. 1 & 2.

The recycling process of Tetra Pak beverage cartons basically involves the carton being opened, cleaned, disintegrated and separated in a hydropulper (a big blender) which is analogous to the conventional pulper used for recycling wastepaper, with a simple modification of installing a drilled plate under the hydropulper rotor which allows the pumpable fibre slurry to move out through a designated outlet, leaving behind the low density polyethylene/aluminum foil residues in the hydropulper container (Tetra Pak Corporate Environmental Affairs (CEA), 2000). The hydropulpers employed for carton recycling can be classified based on operating processes (batch or continuous) and rotor types (low, medium or high consistency rotors). While continuous process can be explicitly used in wastepaper recycling, it is to be avoided as much as possible in beverage carton repulping, except when large amount of wastepaper are blended with the cartons before disintegration (Abreu, 2000).

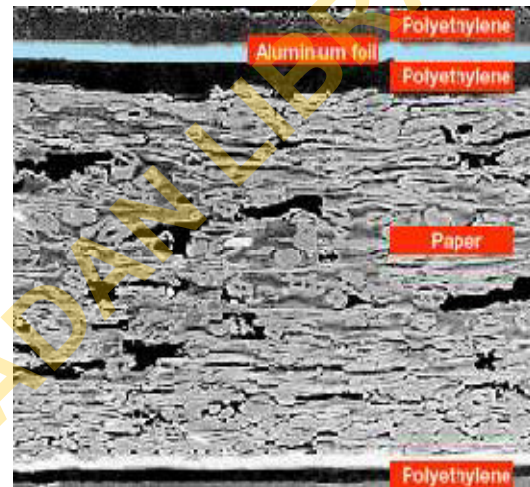
The low consistency rotor is specifically suited for fast repulping action, with the fibres usually cut during the process (rotor-to-fibre interaction) leading to low value final product, while the high consistency rotor were developed later to pulp stock at higher shearing action (fibre-to-fibre interaction) in a smooth and gentle repulping process, though in a longer time than low consistency rotors (Tetra Pak CEA, 2000). The medium consistency rotors are hybrid rotors used to compromise the highs and lows of the two rotor types. In addition, the proportions of cartons repulped in water are also classified as low consistency (3-5% carton), medium consistency (6-9% carton) and high consistency (12-15% carton). Contrary to intuition, the addition of temperature or chemicals to the repulping process does not have any significant effect on the overall performance of the recycling action.

The practice of using recycled fibres from Tetra Pak<sup>®</sup> beverage cartons for papermaking was commercially reported in the late 90's in Brazil and USA; a practice that has since extended to other developed countries of the world (Abreu, 2002). Pablo (2009) reported Lloyd Alter to have said that only 18% of Tetra Pak<sup>®</sup> cartons are recycled worldwide; a figure which has gradually increased to about 30% (i.e. an increase of 73%) in the past seven years due to Tetra Pak's drive towards recyclability of their products. In developing countries however, many communities still struggle to divert their postconsumer disused Tetra Pak beverage cartons from their waste streams (Stearns, 2013), thereby causing environmental pollution and ugly sights in landfills and open dumpsites. In these communities, there are no proper waste collection systems and

particularly there is no existence of recycling facilities to process these cartons into other usable products. One of such communities is Nigeria, as no commercial breakthrough of Tetra Pak<sup>®</sup> carton recycling has been recorded over the years. Hence, there is a need to separately collect Tetra Pak beverage cartons from household waste and locally fabricate a machine, which will be cost effective, not complex to operate and easy to maintain, to recover quality fibres from these cartons so as to meet the growing demand for paper products.



**Fig. 1: Arrangement of Layers in a Tetra Pak Carton**



**Fig. 2: The Microstructure of a Tetra Pak Carton from Inside-Out**

*Source: Abreu, 2000*

## METHODOLOGY

### Design of the Hydrapulper

The design of the hydrapulper was adapted from several literatures (Abreu, 2000; Tetra Pak CEA, 2000; Zhengzhou Guangmao ZDSD 23 Hydrapulper). The design was based on the availability of materials for the fabrication, which were locally sourced at metal-scrap markets to make the equipment cost-effective and easy to operate. The materials include 4mm thick and 50mm wide angle irons, 2mm thick mild steel plates, 2mm thick rectangular iron pipes, 2mm and 3mm thick circular iron pipes, a gate valve, a 1.5:1 speed reduction gearbox and a 2hp electric motor.

### Design Considerations and Parameters

1. The hydrapulper cylindrical container was designed to be strong enough to withstand the internal stresses that might develop inside the container through the collision of the agitated water-diluted stock with the wall of the container.
2. Mild steel and angle iron were used as the major constructional materials because they are readily available, possesses adequate strength and can be easily formed and joined together through screwing and welding.
3. The base of the container was made to slightly taper uniformly towards its center to facilitate easy discharge of the pulp slurry by preventing settling of recycled fibres at the edges of the base of the container.

4. Three vertical triangular baffles made from angle iron were welded to the wall of the container at equal distance from one another to improve the disintegration process.
  5. An electric motor which powers a gearbox through a rotating shaft. A high consistency rotor blade, attached to the shaft, was used to promote high shear action and smooth repulping in order to produce high quality fibres.
  6. The overall height of the hydrapulper was ergonomically chosen to improve its stability during repulping processes, to provide the operator with maximum comfort during usage and to facilitate general maintenance and cleaning of the inside of the hydrapulper.
  7. The six supporting legs, which carry the weight of the container and its content, were made of circular hollow pipes to maintain rigidity of the hydrapulper on the ground during operation.
  8. The machine was painted with silver grey colour to prevent corrosion and improve its aesthetics.
- Some of the basic parameters considered during the design of the hydrapulper are shown in Table 1.

**Table 1: Basic Parameters Considered during the Design of the Hydrapulper**

Known Parameter	Value
Capacity of the hydrapulper	80litres (0.08m <sup>3</sup> )
Height of the container	500mm
Rotor blade type	High consistency rotor
Maximum output torque	15Nm
Minimum speed of rotation of the shaft	500rpm
Yield strength of mild steel	250MPa (Craig, Jr. 1996)
Modulus of Rigidity of mild steel	80GPa (Craig, Jr. 1996)
Maximum shear stress for mild steel	55MN/m <sup>2</sup> (Hall <i>et al</i> , 1980)
Atmospheric pressure	101325N/m <sup>2</sup>
Density of water	1000kg/m <sup>3</sup>
Acceleration due to gravity	9.81m/s <sup>2</sup>

## Design of the Hydrapulper Components

### (a) Diameter of the Container

The container houses the rotor blade attached to a rotating shaft which is powered by a gearbox connected to an electrical motor. The rotation of this blade causes the disintegration of the water-diluted stock. Since the hydrapulper is of laboratory-scale, the maximum capacity of the container is limited to 0.08m<sup>3</sup> (80litres) with an overall height of 500mm to facilitate comfortable operation, cleaning and maintenance. The diameter of the container is calculated from the volume of a cylinder through the relation given in equation (1).

$$\text{Volume of a cylinder, } V = \frac{\pi D_i^2 h}{4} \quad \dots \dots (1)$$

where  $D_i$  = internal diameter of the container

$h$  = height of the container

$$\therefore D_i = \sqrt{\frac{4V}{\pi h}} = \sqrt{\frac{4 \times .08}{\pi \times 0.5}} = 0.4514\text{m}$$

$$D_i \cong 0.45\text{m} = 450\text{mm}$$

Therefore, the internal diameter of container is 450mm.

**(b) Thickness of the Wall of the Container**

The container is treated as being made of a thin section since the built-up pressure inside the container occurs by the virtue of water-diluted stock it houses as well as the agitation of the stock during disintegration processes.

For a thin – walled cylinder,

$$\frac{2t}{R_i} < 0.1 \quad \dots \dots \dots (2) \quad (\text{Collins } et \text{ al, 2010})$$

where  $t$  = thickness of the cylinder

$$\therefore t < \frac{0.1 \times D_i}{2}$$

$$t < \frac{0.1 \times 450}{2} < 22.5 \text{mm}$$

Thus, the thickness of the wall of container must be less than 22.5mm.

Assuming the container is opened to the atmosphere and filled to capacity with water, the maximum built-up pressure inside the cylinder is given as

$$\text{Maximum Pressure, } P_{\max} = P_{\text{atm}} + \rho g(h_1 - h_2) \quad \dots \dots \dots (3) \quad (\text{Aperabo, 2007})$$

where  $P_{\text{atm}}$  = atmospheric pressure = 101325N/m<sup>2</sup>

$\rho$  = density of water = 1000kg/m<sup>3</sup>

$g$  = acceleration due to gravity = 9.81m/s<sup>2</sup>

$h_1 - h_2$  = height of the container = 500mm = 0.5m

$$\therefore P_{\max} = 101325 + 1000 \times 9.81 \times 0.5$$

$$P_{\max} = 106230 \text{N/m}^2 = 1.06 \times 10^5 \text{N/m}^2$$

To accommodate for the forces arising from the disintegrating action of the rotor blade and the pressure created through the collision of the stock with the wall of the container, a factor of safety of  $n = 5$  was chosen for the design. Thus the working stress of the container made of mild steel is given as

$$\text{working stress, } \sigma_{ws} = \frac{\sigma_{yp}}{n} \quad \dots \dots \dots (4)$$

where  $\sigma_{yp}$  = yield stress of mild steel = 250MPa

$$\therefore \sigma_{ws} = \frac{250 \times 10^6}{5} = 5 \times 10^7 \text{N/m}^2$$

For a thin-walled cylindrical vessel, the tangential stress (working stress) is given as

$$\text{Tangential stress, } \sigma_{ws} = \frac{P_{\max} \times D_i}{2t} \quad \dots \dots \dots (5) \quad (\text{Collins } et \text{ al, 2010})$$

$$\therefore t = \frac{P_{\max} \times D_i}{2 \times \sigma_{ws}} = \frac{1.06 \times 10^5 \times 0.45}{2 \times 5 \times 10^7} = 4.77 \times 10^{-4} \text{m}$$

$$t = 0.477 \text{mm}$$

Hence, a mild steel plate of 2mm thickness was used for the fabrication of the hyrapulper container.

**(c) Vertical Baffles**

Three vertical baffles made with 50mm angle iron of 4mm thickness and 400mm length are installed internally at equal distance from one another around the internal wall of the container. The distance between the baffles is computed through the relation of the circumference of a circle as given in equation (6).

$$\text{Circumference, } C = \pi D_i \quad \dots \dots \dots (6)$$

$$\text{i. e } C = \pi \times 450 = 1413.72 \text{mm}$$

$$\text{Number of baffles, } N_b = 3$$

$$\therefore \text{Position of the baffles from one another} = \frac{C}{N_b}$$

$$\text{Baffles position from one another} = \frac{1413.72}{3} = 471.24\text{mm}$$

Thus, the baffles are positioned at about 470mm distance from one another circumferentially around the internal wall of the container.

**(d) Power Requirement**

With a desired maximum output torque of 15Nm, a medium speed electric motor of 1440rpm. is required to power a gearbox system of 1.5:1 gear reduction ratio which in turn rotates the shaft on which the rotor blade is attached.

The output torque (torsion moment) of the gear reducer is given as

$$T_{out} = \frac{30P}{\pi n_m} u_g k_s \quad \dots \dots \dots (7) \quad (\text{Zdziennicki and Maciejczyk, 2014})$$

Where,

P = Electric motor power

Output torque = 15Nm

Motor rotational speed,  $n_m = 1440\text{rpm}$ .

Gear reduction ratio,  $u_g = 1.5: 1$

$k_s$ =service factor; which is given as

$$k_s = k_a \times k_t \quad \dots \dots \dots (8) \quad (\text{Zdziennicki and Maciejczyk, 2014})$$

where  $k_a$  = application factor and  $k_t$  = duty factor

Assume the gear input operating conditions as uniform and output operating conditions as moderate shock, the application factor  $k_a=1.25$ . Also, if the gear reducer is running for 10hrs/day, the duty factor  $k_t=1.0$ .

$$\therefore T_{out} = \frac{30P}{\pi \times n_m} u_g \cdot k_a \cdot k_t \quad \dots \dots \dots (9)$$

$$P = \frac{T_{out} \times \pi \times n_m}{30 \times u_g \cdot k_a \cdot k_t}$$

$$P = \frac{15 \times 3.142 \times 1440}{30 \times 1.5 \times 1.25 \times 1.0}$$

$$P = 1206.5\text{W} = 1.21\text{kW}$$

since  $1\text{kW} = 1.34\text{hp}$ , then  $1.21\text{kW} = 1.21 \times 1.34 = 1.62\text{hp}$

Thus, an electric motor of 2hp was chosen to drive the gearbox.

**(e) Shaft Diameter**

To design the shaft based on strength, the American Society of Mechanical Engineers (ASME) design code for ductile material (mild steel) is employed. The general relation is given in equation (10).

$$\tau_{allowable} = \frac{16}{\pi d_0^3 (1-c^4)} \sqrt{\left( k_m M + \frac{\alpha F_a d_0 (1+c^2)}{8} \right)^2 + (k_t T_{out})^2} \quad \dots \dots \dots (10) \quad (\text{Hall, et al, 1980})$$

Where  $k_m$  and  $k_t$  are bending and torsion factors to account for shock and fatigue.

Since the shaft is subjected primarily to only torsion effect, with no bending load and negligible axial load (due to weight of the rotor blade), the design of the shaft is based on a limiting factor of shear stress generated by twisting moment only. The bending and axial stress term is reduced to zero (as bending moment,  $M=0$  and axial load,  $F_a = 0$ ). Therefore, equation (10) is simplified to

$$\tau_{\text{allowable}} = \frac{16}{\pi d_0^3 (1-c^4)} k_t T_{\text{out}} \quad \dots \dots \dots (11)$$

Where,

$\tau_{\text{allowable}}$  = permissible shear stress based on twisting effect of the shaft

$d_0$  = outside diameter of the shaft

$c = d_i/d_0$  = ratio of the internal diameter to outside diameter of the shaft

For a solid shaft,  $c=0$  since the internal diameter  $d_i=0$ .

Thus, equation (11) is simplified further to

$$\tau_{\text{allowable}} = \frac{16}{\pi d_0^3} k_t T_{\text{out}} \quad \dots \dots \dots (12)$$

Re-arranging equation (12), the diameter of the solid shaft is given as

$$d = \sqrt[3]{\frac{16}{\pi \times \tau_{\text{allowable}}} k_t T_{\text{out}}} \quad \dots \dots \dots (13)$$

where  $d$  = diameter of the solid shaft, m

$\tau_{\text{allowable}}$  = allowable shear stress of the shaft, N/m<sup>2</sup>

$k_t$  = combined shock and fatigue factor applied to torsional moment

$T_{\text{out}}$  = torsional moment (or output torque), Nm

For commercial steel shafting without keyways,

The maximum shear stress,  $\tau_{\text{max}} = 55 \text{ MN/m}^2$  or  $55 \text{ N/mm}^2$ .

Using a factor of safety of  $n=4$  to accommodate for excessive loading of the shaft during operation, the allowable (working) shear stress,  $\tau_{\text{allowable}}$  is given as

$$\tau_{\text{allowable}} = \frac{\tau_{\text{max}}}{n} \quad \dots \dots \dots (14)$$

$$\tau_{\text{allowable}} = \frac{55}{4} = 13.75 \text{ N/mm}^2$$

For a rotating shaft with load suddenly applied (minor shock),  $K_t = 1.5$  (Hall *et al*, 1980)

Torsional moment,  $T_{\text{out}} = 15 \text{ Nm} = 1.5 \times 10^4 \text{ Nmm}$

Substituting the known parameters in equation (13), the diameter of the shaft is computed thus

$$d = \sqrt[3]{\frac{16}{\pi \times 13.75} \times 1.5 \times 1.5 \times 10^4} = 21.74 \text{ mm}$$

$$\therefore d = 20.27 \text{ mm}$$

Thus, a standard size of 25mm diameter shaft was selected based on availability.

To design for torsional rigidity based on the permissible angle of twist, the amount of twist permissible for a machine tool is 0.3deg. per unit length of the shaft.

For a solid shaft,

$$\text{permissible twist, } \theta/L = \frac{584 T_{\text{out}}}{G d^4} \quad \dots \dots \dots (15) \quad (\text{Hall } et \text{ al}, 1980)$$

where,  $L$  = length of the solid shaft

$G$  = Modulus of rigidity

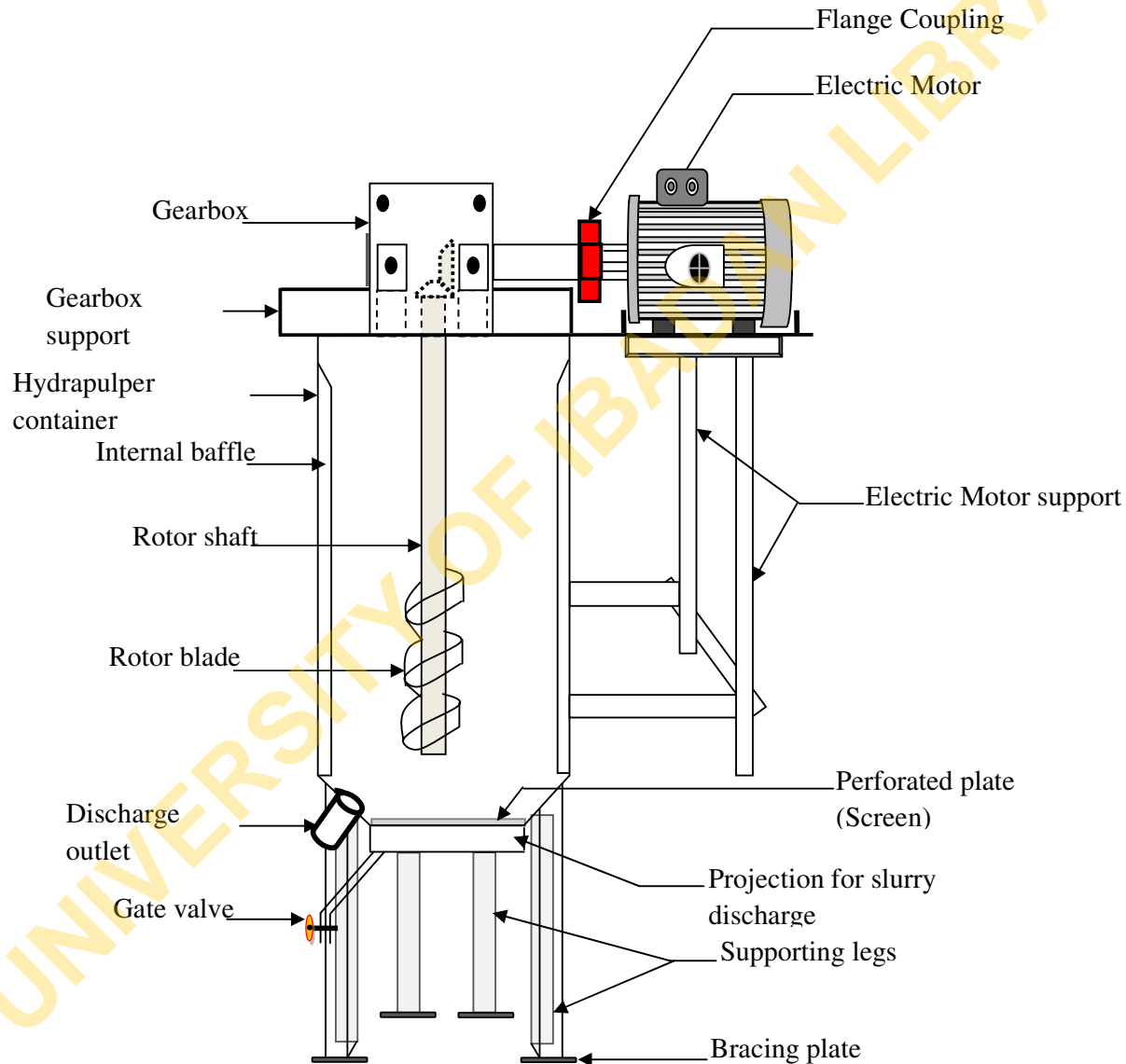
For a steel shafting,  $G = 80 \text{ GN/m}^2$

$$\theta/L = \frac{584 \times 15}{80 \times 10^9 \times 0.025^4} = 0.28 \text{ deg./m}$$

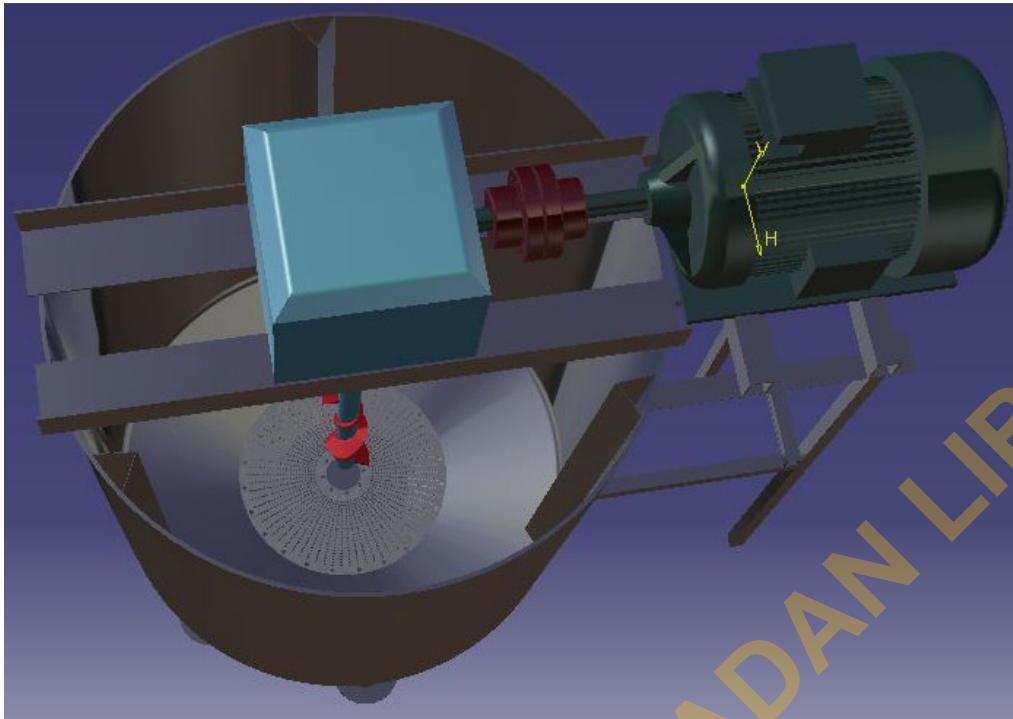
Hence, since the induced twist (0.28deg./m) in the shaft is less than the allowable twist (0.3 deg./m) acceptable in a machine tool, the design is safe under rigidity.

**Fabrication and Assembly**

The hydrapulper was fabricated at ISOLTEC Technical Workshop, Ibadan. The major processes undertaken during the fabrication were grinding, marking out, cutting, beating, welding, sharpening, drilling and boring, from which the cylindrical container, the rotor blade, the container cover and the hydrapulper legs were fabricated and assembled together. The schematic diagram and the bird’s eye view of the hydrapulper assembly are shown in Fig. 3 and 4 respectively.



**Fig. 3: Schematic Diagram of the Hydrapulper**



**Fig. 4: A Bird’s Eye View of the Hydrapulper Assembly**

**Performance Evaluation of the Hydrapulper**

The disused Tetra Pak cartons used for this study were gathered largely from halls of residence in University of Ibadan, with few others collected from event centres and ceremony grounds in Ibadan metropolis. The cartons are of three sizes: 1litres, 500ml and 250ml. They include cartons of Hollandia, 5-alive, Chi Happy Hour, Fresh Yo, Fumman cocktail, Strawberry, Lucozade Boost, Chi Exotic and Fumman Festive, with Tetra Pak® logo at their bottom flaps. The collected cartons were carefully opened along their seams with the aid of a table knife, gently washed with clean water, sun-dried for about 2 – 3 hours and cut into small pieces of 60-80mm long and 50-60mm wide in order to ease the disintegration process. These pieces of cartons were packed in polythene bags and stored in a cool dry place.

The disintegration processes were performed at three different stock consistencies. The stock consistency refers to the amount of cartons diluted per water volume expressed in percentage of the total stock. Mathematically, stock consistency is as given in equation (16).

if C = consistency (%),  $W_c$  = weight of carton (kg) and  $W_w$  = weight of water(kg)

$$\text{then, } C = \frac{W_c}{W_c + W_w} \times 100\% \quad \dots \dots \dots (16)$$

Thus, for a desired consistency and a known weight of water, the weight of carton needed for repulping is as given in equation (17).

$$W_c = W_w \left( \frac{C}{1 - C} \right) \quad \dots \dots \dots (17)$$

Hence, for a 30 litres (30,000cm<sup>3</sup>) of water used for each repulping experiment 0.93kg, 2.6kg and 4.5kg of carton pieces were repulped for low, medium and high consistencies respectively. The yield of the pulp produced, which is the measure of the performance of the hydrapulper can be expressed mathematically as shown in equation (18).

$$\text{pulp yield} = \frac{\text{weight of the pulp produced after disintegration}}{\text{weight of catons repulped}} \times 100\% \dots \dots (18)$$

Each consistency experiment was performed in 3 replicates and the resulting pulp yields were analyzed by Analysis of Variance (ANOVA) at 5% significant level using Microsoft Office Excel 2007 computer software to determine if there is a significant difference in yields obtained at the three consistencies.

## RESULTS AND DISCUSSION

A hydrapulper of 80litres volumetric capacity was designed and fabricated using locally sourced materials and successfully disintegrate and separate the components of disused Tetra Pak beverage cartons. The pulp yield from each experiment under the three consistencies is shown in Table 2.

**Table 2: Results of Average Pulp Yield at Each Consistency**

Replicate	Consistency type		
	Low	Medium	High
1	58.06	61.15	57.56
2	61.29	60.38	56.89
3	62.37	59.23	60.22
<b>Mean</b>	<b>60.57</b>	<b>60.26</b>	<b>58.22</b>

From Table 2, it can be observed that the pulp yields throughout the experiment vary from 56.89% under high consistency to 62.2% under low consistency indicating that about 80% of the paper component of the carton can be recovered using this equipment. The average pulp yields of 60.57%, 60.26% and 58.17% for low, medium and high consistencies respectively indicate that the rate of yield of pulp slightly decreases as the quantity of carton repulped increases; as the highest traces of pulp fibres were seen undetached from the “polyfoil” residues after disintegration of cartons at high consistency. This slight increase in yield at low consistency may be attributed to the low viscosity of water-diluted stock observed during repulping processes, as carton pieces were readily carried with the aid of the internal baffles towards the rotating blade than during repulping processes at high consistency. The result of the pulp yield is in agreement with the 65% reported in Tetra Pak CEA (2000) as the minimum pulp yield of most hydrapulper on commercial scale. The pulp yield can however be increased by the use of rotary drum to separate the remaining traces of fibres from the “polyfoil” residues.

**Table 3: Result of Analysis of Variance (ANOVA) of the Pulp Yields at Each Consistency**

Source of Variation	SS	df	MS	F-value	P-value	F crit.
Between Groups	9.76685	2	4.883425	1.617348	0.274275*	5.143253
Within Groups	18.11642	6	3.019403			
Total	27.88327	8				

\*test not significant at  $p > 0.05$  probability level or  $F\text{-value} < F_{crit}$ .

The result of the analysis of variance of the pulp yields at each consistency (Table 3) indicates that there is no significant difference between the pulp yields at the three consistencies. Thus, the slight difference in the average pulp yields at each consistency may be due to experimental errors that might have occurred during the replication of the experiment and not due to the difference in amount of cartons that were repulped. This means that carton pieces can be repulped at any consistency without any significant differences in the yields of pulp.

## Conclusion and Recommendations

The need to reduce overdependency on forest resources (wood) for papermaking and the utilization of household wastes for the manufacture of paper and other value-added products necessitated the design and fabrication of a laboratory-scale hydrapulper, which disintegrate disused Tetra Pak® beverage cartons, with the highest pulp yield of 60.57% recorded at low consistency repulping. However, there is no significant difference in the yields of pulp obtained at low, medium and high consistencies. It is recommended that sorting and categorization of household wastes should be encouraged in homes and offices to avoid contamination of these cartons with other food waste items usually disposed off in the same waste bins in order to prevent the damage of the cartons and also facilitate easy collection of the cartons for disintegration. The effects of different rotor blades on the yield and quality of pulp produced should also be investigated.

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