Development and Performance Evaluation of a Simple Batch Reactor for Leaching of Potassium Ash

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Abstract-

Leaching is ubiquitous operation for extracting a substance from a solid matrix through interaction between the solid matrix and liquid. Most batch reactors with fairly advanced sophistication are very costly while the less costly ones are of low performance and have quality challenge. The aim of this paper is to develop a simple batch reactor that uses continuous stirred action to leach caustic potash from potassium ash derived from cocoa pod husk. The batch reactor is made up of a hopper for the passage of the feed to the cylindrical vat, variable speed motorized stirrer, filter mesh, basket filter, heating/cooling system, temperature controller, temperature sensor attached to the heating/cooling system. The design has it novelty by the incorporation of temperature controller and sensor to the heating/cooling system. The criteria for the materials selection of the design were strength, corrosion resistance, machinability and economic value. The consideration of the design was based on existing machine design theories. The performance assessment showed that the reactor is capable of leaching caustic potash from potassium ash derived from cocoa pod husk on the basis of 1 Tonne per day. It was discovered that there is a direct relationship between leaching time and mass of caustic potash extracted and an inverse relationship between the leaching time and mass of sludge. At a leaching time of 30 minutes, the mass of the potash leached was 45kg and the mass of sludge was 30kg, whereas, at a time of 45 minutes, the mass of caustic potash increased to 75kg and the mass of the sludge decreased to 25kg. From the evaluation, the efficiency of the machine is 74.14%. The development of a 1ton/day potassium ash leaching reactor was achieved. The machine is useful for processing of caustic potash in reasonable time and quality.

Keyword: Caustic potash, Leaching, Parameters, Reactor, Thermostat

1. Introduction

Leaching is ubiquitous operation for extracting a substance from a solid matrix through interaction between the solid matrix and liquid. There are several by-products generated from the post-harvest processing of cocoa pod which can be turned to other economic products, constituting waste due to lack of appropriate technology [1a-c]. According to the research conducted and reported by Cocoa Research Institute of Ghana (CRIG) in the early 80s, which showed that by-products from processed cocoa pods and cocoa beans could be commercialized. To this effect was the implementation of the ICCO/CFC/CRIG project in Ghana on the development and commercialization of pilot plants for processing cocoa by-products into useful products [1-2]. An example is the production of caustic potash from cocoa pod husks. The cocoa beans constitute only about
19% of the total pod while the remaining 81% forms the cocoa pod husk (CPH) [1a-c]. Harnessing the pod husk as a source of caustic potash will not be a constraint in terms of raw material availability, more so, caustic potash produced from pod husk serves as useful laboratory reagent for domestic and industrial purposes [3]. Production of caustic potash is a result of an extraction chemical process between pod ashes and water known as leaching. The husk is the major component of cocoa pod, constituting about 56% of the total mass of the pod [4]. However, the major challenge of the leaching process boils down to the development of a suitable processor for the conversion of the husk to caustic potash. Unfortunately, most processors with fairly advanced sophistication are very costly while the less costly ones are of low performance and have quality challenge. Few researchers have reported on the production of caustic potash via leaching, thus there is dearth of information on the leaching mechanism and processing. Daniyan et al. [3], reported annual production of 30,000 tonnes of caustic potash from cocoa pod husk based on the design of a single processor comprising of the detailed energy and material balance as well as analysis of instrumentation and control. Also, Daniyan et al. [5] further improved on the work by design and modelling an automated reactor for the same process using ASPEN HYSYS as a process model tool in order to achieve the material and energy optimization as well as the plant economics. The design of the system incorporates an Arduino uno Microcontroller and temperature sensor to monitor the process conditions of the reactor. The analysis of integration features of the overall process for caustic potash production from single or multi locally sourced feedstock has remain a major challenge coupled with the expensive cost of the relatively advanced technologies batch reactor. This work is aimed at developing a simple low-cost batch reactor of 1 tonne per day capacity for leaching of potassium ash derived from cocoa pod husk and can be adopted in developing nations like Africa without compromising the quality of the final product.

2. Materials and Method

The identification and selection of the essential materials used in the study were based on the following criteria, strength, durability, machinability and availability in the local market. The conceptual and detailed design of the machine using existing design theories were also carried out. The fabrication procedures adopted for the machine development include measuring, marking-out, cutting, shaping, folding, drilling, turning, machining and welding.

2.1 Materials Selection of the Components of the Machine

Material properties such as bulk density, cost, availability, corrosion resistance, tensile strength, rigidity, weldability, and machinability, were duly considered before selection for the fabrication.

2.1.1 Material for the frame

The frame is made of 4 mm mild steel angle iron. It was cut the required dimensions with the aid of angle grinder. The length, breadth and height are 700 mm, 700 mm and 760mm respectively. Following the design as shown in Figure 1, the cut members were welded together using arc welding with mild steel electrode.
2.1.2 Material for cylindrical vat
The Cylindrical vat is made of 4mm thick stainless steel sheet. After cutting the sheet to the required dimension, it was rolled on rolling machine to form a cylindrical shape as shown in Figure 2. The diameter and height of the vat are 598 mm and 760 mm respectively. The base was covered with a circular plate of 598 mm diameter. Stainless steel electrode was used for the welding process.

2.1.3 Materials for the hopper
The hopper is the inlet opening through which the cocoa pod husk is fed into the cylindrical vat. It is made of 4 mm stainless steel as the cylindrical vat. It is welded to the top cover of the cylindrical vat which is bolted to the vat. The design of the hopper is shown in the Figure 3.
2.1.4 Material for the bearings
The bearing selected is mild steel flange bearing of 2 mm diameter which accommodates the rotating shaft and for the purpose of balancing the rotating stirrer.

2.1.5 Material for the mesh plate
The mesh is a circular perforated plate made of stainless steel. The perforation serves as sieve which allows the filtrate of the burnt coca pod husk to be collected through the exit pipe of the cylindrical vat.

2.1.6 Material for the stirrer Assembly
The stirrer is made of shaft, blade, bolts and nuts. The shaft is a stainless material of 25mm diameter and the blade is made of from 4mm thick stainless plate. A stirrer support, made from same stainless material, is used as support for the shaft for rotational stability. The detailed design is shown in Figure 4.

2.1.7 Filter Mesh
The filter mesh is made of stainless steel materials of 2 mm thickness. It is a perforated circular plate of 582 mm diameter. The design is shown in the Figure 5.
2.1.8 Basket Filter

The basket filter is made from 4 mm thick stainless-steel plate. It houses fine sand for filtering purpose. The design is presented in the Figure 6.

![Figure 5: Design of the Filter Mesh](image)

![Figure 6: The Basket Filter](image)

2.2 Design Considerations

The design analysis spells out the details about the parameters to be used for the construction and fabrication of the machine for the potash production. The equations 1 to 43 are used for design analysis as given by [6]

2.2.1 Design of the Belt Drive

\[
\text{Belt velocity}, \quad v = \frac{\pi D_2 N_2}{60} \tag{1}
\]

- \(D_2 = \text{diameter of the motor pulley} = 0.1 \text{ m}\)
- \(N_2 = \text{speed of the motor} = 1405 \text{ rev/min}\)
\[ v = \text{velocity (m/s)} \]
\[ v = \frac{2 \times 0.1 \times 1405}{60} = 7.36 \text{ m/s} \]  
(2)

2.2.2 Determination of the Speed and Diameter of the Big/Machine Pulley

Note: Speed ratio = 3:1

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

Where:
- \( D_1 \) = Diameter of the Machine Pulley
- \( D_2 \) = Diameter of the Electric Motor pulley
- \( N_1 \) = speed of the Big Pulley
- \( N_2 \) = speed of the smaller pulley

\[ \frac{3}{1} = \frac{N_2}{N_1} \]  
(4)

\[ N_1 = 460 \text{ rev/min} \]

\[ D_1 = \frac{N_2 D_2}{N_1} = \frac{1405 \times 0.2}{460} \]  
(5)

\[ D_1 = 300 \text{ mm} = 0.3 \text{ m} \]

2.2.3 Determination of the Torque Transmit on the Motor

\[ T_s = \frac{60P}{2\pi N_2} \]  
(6)

Where
- \( T_s \) = Torque on the motor
- \( P \) = Power on the motor = 3.7 kW
- \( N_2 \) = speed on the motor = 1405 rev/min

\[ T_s = \frac{60 \times 3.7 \times 1000}{2\pi \times 1405} = \frac{222000}{8829.02} = 25.14 \text{ Nm} \]  
(7)

2.2.4 Determination of the Tension on Belt

\[ T_s = (T_1 - T_2) \frac{D_2}{2} \]  
(8)

where;
- \( T_1 \) = Tension in the tight side of the belt
- \( T_2 \) = Tension in the slack side of the belt
- \( D_2 \) = Diameter of the smaller pulley = 0.1m

\[ 25.14 = (T_1 - T_2) \frac{0.1}{2} \]  
(9)

\[ T_1 - T_2 = 502.8 \text{ N} \]  
(10)

Note:

\[ \frac{T_1}{T_2} = 3 \text{ Assumed belt tension} \]  
(11)

\[ T_1 = 3T_2 \]  
(12)

Substitute \( 3T_2 \) for \( T_1 \) in

\[ T_1 - T_2 = 502.8 \text{ N} \]  
(13)

\[ 3T_2 - T_2 = 502.8 \text{ N} \]  
(14)

\[ 2T_2 = 502.8 \text{ N} \]  
(15)

\[ T_2 = 251.4 \text{ N} \]  
(16)
Since
\[ T_1 = 3 \times 251.4 = 754.2 \text{ N} \]

(16)

\[ T_4 = 3T_2 \]

\[ T_L = (T_1 - T_2)\frac{D_1}{2} \]

(17)

Where:
- \( T_L \) = Torque on the Machine
- \( T_1 \) = Tension in the tight side of machine
- \( T_2 \) = Tension in the slack side of the belt
- \( D_1 \) = Diameter of the Larger Pulley = 0.3 m
- \( T_L = (754.2 - 251.4)\frac{0.3}{2} = 75.42 \text{ Nm} \)

(18)

2.2.6 Determination of Power Transmit on Machine

\[ P_m = T_L \times \frac{2\pi N_1}{60} \]

(19)

Where:
- \( P_m \) = power of the Machine
- \( N_1 \) = Speed of the Machine = 468 rev/min
- \( P_m = 75.42 \times \frac{2\pi \times 468}{60} \)
- \( P_m = 3696.73 \text{ W} = 3.69673 \text{ kW} \)

(20)

2.2.7 Determination of Efficiency on the Belt Drive

\[ \text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} \times 100 \]

\[ \text{Efficiency} = \frac{369673}{3.7} \times 100 = 99.91 = 99.91\% \]

(21)

(22)

2.2.8 Determination of Power Lost in Friction

\[ \text{power lost in Friction} = \text{power input} - \text{power output} \]

\[ P_f = P_m - P_{out} \]

Power lost in friction = 3.700 - 3.69673 = 0.0033 kW

(23)

2.2.9 Centre to Centre Distance between the Pulleys

Where:
- \( D_1 \) = Diameter of the Larger Pulley = 0.3m
- \( D_2 \) = Diameter of the Smaller Pulley = 0.1m
- \( C \) = Centre to Centre Distance (m)

\[ C = \frac{1}{2}(D_1 - D_2) + D_1 \]

(24)

\[ C = \frac{1}{2}(0.3 - 0.1) + 0.3 = 0.4 \text{ m} \]

(25)

\[ C = 400 \text{ mm} = 0.4 \text{ m} \]

2.2.10 Determination of Belt Length

\[ L = \frac{1}{2}(D_1 + D_2) + 2C + \left(\frac{D_1 + D_2}{4C}\right)^2 \]

(26)

Where:
2.2.11 Determination of Angle of Contact or Lap

When two pulleys of different diameters are connected by a means of an open belt as shown in Figure 10, then the Angle of contact or lap is thus calculated;

\[
\sin \beta = \frac{(D_1 + D_2)}{2C} 
\]

Therefore, for small pulley consideration:

\[
\sin \beta = \frac{0.3 + 0.1}{2 	imes 0.4} = 0.25 
\]

\[
\beta = \sin^{-1} 0.25 = 14.49^\circ 
\]

For larger pulley considerations:

\[
\beta = (180^\circ - 2\beta) 
\]

\[
\theta = (180^\circ - 2 \times 14.49^\circ) = 151.04^\circ 
\]

\[
\theta = (180^\circ + 2\beta) 
\]

\[
\theta = (180^\circ + 2 \times 14.49^\circ) = 208.96^\circ 
\]

2.2.12 Cylindrical Vat Design

The cylindrical vat's volume is thus calculated using the formula of an open cylinder.

\[
V = \pi r^2 h 
\]

Where, \( h = 765 \text{ mm} = 0.765 \text{ m} \)
\( r = 295 \text{ mm} = 0.295 \text{ m} \)
\( V = \pi \times 0.295^2 \times 0.765 = 0.209 \text{ m}^3 \)

2.2.13 Shaft Design

The rigidity of the shaft is a good factor to consider for load transmission under various operating conditions. To achieve this, a solid circular shaft was considered to take care of both torsional and bending stresses.

The diameter of a solid shaft under no axial load, is given by equation 38:

\[
d^2 = \frac{16}{\pi^2} \left[ (k_bM_b)^2 + (k_tM_t)^2 \right]^{1/2} 
\]

Where,
\( M_t \) = torsional moment,
\( M_b \) = bending moment
\( K_b \) = combined shock and fatigue applied to bending moment (1.5)
\( K_t \) = combined shock and fatigue applied to torsional moment (1.0)
\( S_\alpha \) = allowable stress.

\[
Torque, T = \frac{Power}{\omega} 
\]

\[
\omega = \frac{2\pi N}{60} 
\]

\[
Torque, T = \frac{P}{\omega} = \frac{P \times 50}{2\pi N} 
\]
where, $\tau = \text{permissible shear stress of the shaft material}$

$$T_e = \sqrt{M^2 + T^2}$$

where $M = \text{Maximum Bending moment}$

The specification parameters and values for the construction and fabrication of the machine for the potash production as shown in Table 1.

| Parameter                      | Values       |
|--------------------------------|--------------|
| Height of Cylindrical Vat      | 0.765 m     |
| Diameter of Cylindrical Vat    | 0.590 m     |
| Volume of Cylindrical Vat      | 0.209 m$^3$ |
| Diameter of the stirrer Shaft  | Ø 25 mm     |
| Height of the stirrer Shaft    | 0.675 m     |
| Speed of electric motor        | 1405 rpm    |
| Speed of Machine driven        | 468 rpm     |
| Motor power rating             | 5 Hp        |

2.3 Components Assembling Process

The assembly of all the components of the leaching reactor as described in Figures 1-6 above is presented in Figure 7.
3. Performance Evaluation

The electric motor supplies power to the machine and put it to operation. Ash, made from cocoa pod husk, is fed to the cylindrical vat and water is fed as well at a moderate volume. As the stirrer assembly rotates, it agitates the mixture content in the vat. The mixture passes through the fine mesh, filter sand and the filter basket. The filtrate then comes out through the outlet of the cylindrical vat.

3.1 Chemical Composition of Cocoa Pod Husk and KOH Physical Property

The Chemical Composition of Cocoa Pod Husk and physical property of KOH were adapted from [7-8] as shown in Tables 2 and 3.

Table 2: Chemical Composition of Cocoa Pod Husk

| S/N | Constituents of Cocoa Pod Husk | % Composition of Constituents |
|-----|--------------------------------|-------------------------------|
| 1   | Water                          | 57.75                         |
| 2   | Total Dry Matter               | 42.25                         |
|     | **Total**                     | **100**                       |
| 1   | Crude Protein                  | 8.69                          |
| 2   | Pure Protein                   | -                             |
| 3   | Fatty Substance                | 0.15                          |
| 4   | Ash (SiO₂ free)                | 10.80                         |
| 5   | Crude Fibre                    | 33.90                         |
| 6   | Nitrogen-free extracts         | 41.21                         |
| 7   | Glucose                        | 1.61                          |
| 8   | Sucrose                        | 0.18                          |
| 9   | Pectin                         | 3.71                          |
| 10  | Theobromine                    | 0.20                          |

Source: [7]

Table 3: Physical Property KOH

| Property                  | KOH solid (90 %) | KOH aqueous Solution (50 %) |
|---------------------------|-----------------|-----------------------------|
| Physical state            | Solid           | Liquid                      |
| Colour                    | White           | Colourless                  |
| Density at 20 °C (g/cm³)  | 2.044 (fused solid) | 1.5                        |
| Melting Temperature (°C)  | 406             | 6                           |
| Boiling temperature (°C)  | 1327            | 145                         |
| Molecule weight (g/mol)   | 56.1            | -                           |

Source: [8]
4. Results and Discussions

The results of the performance evaluation of the machine as shown in table 4.

Table 4: Performance Evaluation Results

| S/N | Mass of Ash (kg) | Volume of Water added (m³) | Mass of Water Added (kg) | Total Mass (kg) | Leaching Time (mins) | Mass of Potash Leached (kg) | Mass of Sludge (kg) |
|-----|-----------------|---------------------------|-------------------------|-----------------|----------------------|---------------------------|-------------------|
| 1   | 25.00           | 0.05                      | 50                      | 75.00           | 30.00                | 45.00                     | 30.00             |
| 2   | 25.00           | 0.05                      | 50                      | 105.00          | 45.00                | 75.00                     | 30.00             |
| 3   | 25.00           | 0.05                      | 50                      | 105.00          | 45.00                | 80.00                     | 25.00             |
| 4   | 25.00           | 0.05                      | 50                      | 100.00          | 60.00                | 83.00                     | 20.00             |
| 5   | 25.00           | 0.05                      | 50                      | 100.00          | 60.00                | 84.00                     | 18.00             |
| 6   | 25.00           | 0.05                      | 50                      | 93.00           | 60.00                | 55.00                     | 28.00             |
| 7   | 25.00           | 0.05                      | 50                      | 110.00          | 60.00                | 78.00                     | 25.00             |
| 8   | 25.00           | 0.05                      | 50                      | 105.00          | 60.00                | 80.00                     | 20.00             |
| 9   | 25.00           | 0.05                      | 50                      | 95.00           | 60.00                | 85.00                     | 10.00             |
| 10  | 25.00           | 0.05                      | 50                      | 85.00           | 60.00                | 86.00                     | 5.00              |

The efficiency of the machine used to produce the potash was determined as expressed in the equation (45).

\[
\begin{align*}
\text{Total Mass of Potash Leached} & = 751 \\
\text{Total Mass of Water} + \text{Ash} & = 1013
\end{align*}
\]

\[
\text{Efficiency of the machine} = \frac{\text{Total Mass of Potash Leached}}{\text{Total Mass of Water} + \text{Ash}} \times 100 \tag{44}
\]

\[
\text{Efficiency of the machine} = \frac{751}{1013} \times 100 = 74.14 \%	ag{45}
\]

4.1 Discussions

The graph of leaching time against the mass of potash leached was plotted to show the relationship between the two variables as illustrated in Figure 8. It is observed from the batch process that there is a continuous increase in the mass of potash leached as the time progresses [9]. At some point, there was a slight drop in the mass of potash leached as a result of the decrease in the quantity of leached sludge.
The variation in potash extracted was analysed to show the disparity in the extraction after the leaching time as presented in Figure 9. It could be seen that from the batch process, there was a continuous decrease in the mass of sludge; at some point, there was a slight increase in the mass of sludge leached as a result of the fact that the quantity of leached sludge was totally exhausted in the recycling process [9].

Figure 8: Grinding Time versus Ash Cocoa Pod Weight

Figure 9: Leaching Time versus Mass of Sludge

5. Conclusions

A potassium ash leaching batch reactor was designed and fabricated using locally sourced materials. The simple batch reactor has the capacity of 1 tonne per day and leaching efficiency of 74 %. The leaching batch reactor is an indigenous technology with less capital intensive compared to the imported ones. The reasonable efficiency of 74 % indicates that
both service and functional requirements were not compromised. The machine find suitable application in small scale potash ash leaching both in less developed and urban cities.

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