

Design of a Percolation Reactor for the Hydrolysis of Lignocellulosic Biomass

Isaac Femi Titiladunayo, Olayinka Ahmed Ibitowa

Department of Mechanical Engineering, School of Engineering and Engineering Technology, The Federal University of Technology Akure, Akure, Nigeria
Email: ftitiladunayo@yahoo.com

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Abstract

A Percolation reactor for the thermochemical pre-treatment of lignocellulosic biomass as a precursor for the production of biofuel such as bioethanol from complex organic polymers is developed by this study. The reactor is designed to hold 3 kg of pulverised biomass of $0.5 \leq$ and ≥ 0.3 mm particle size for each hydrolysis run, while the mass of other biomass is determined on the basis of density. It consists of a perforated material holding basket which is 0.0261 m^3 in volume, a circulation pump with a power rating of 1.83 W capacity and a heating chamber containing 3 kW heater. The reactor is designed to operate within the temperature range of $20^\circ\text{C} - 180^\circ\text{C}$, pressure $\leq 45 \text{ N}\cdot\text{m}^{-2}$, and desired hydrolysis flow rate of $4.33 \times 10^{-4} \text{ m}^3\cdot\text{s}^{-1}$. The Percolation reactor produced high sugar yield with instant discharge of sugar products after each completed hydrolysis cycle, thus minimizing sugar decomposition. The efficiency of the percolation reactor was determined to be $64.4\% \pm 2\%$ in the hydrolysis of biomass such as cassava peelings to simple sugar. The reactor is therefore a useful tool at converting lignocellulosic biomass to fermentable sugar with high sugar concentration in solid/liquid ratio.

Keywords

Lignocellulosic Biomass, Percolation Reactor, Bioethanol, Biodegradation, Catalyst

1. Introduction

Biofuels (bioethanol) can be produced from biomass feedstocks that are rich in simple sugar such as sucrose, fructose and galactose (e.g. sugarcane) and starchy materials such as plant grain and tubers through direct biodegradation process called fermentation. The use of food crops for fuel production is said to compete

with food security; leaving researchers with the option of utilising lignocellulosic biomass with complex organic structures for conversion to fuels ethanol through biological processes. The crops that are categorized as lignocellulosic biomass include maize husk, cassava peelings, wheat straws, guinea corn husk, rice husk, millet husk, sawdust and sorghum plant, which cannot be converted directly to bioethanol but have to undergo the process of chemical hydrolysis to convert their complex organic content to fermentable simple sugar. The provision of an adequate environment and pre-conditions for enabling chemical hydrolysis of these biomass wastes for biofuel production e.g. bioethanol is the object of this work. Hence, a percolation reactor is developed for the thermochemical degradation of the cellulose, hemicellulose and the lignin structure of biomass wastes to fermentable sugars.

Many researchers have reported on the use of various reactor such as Stir-tank, Plug flow and Batch reactors for the hydrolysis of biomass. Batch reactor has been the most widely used in the kinetic study of hydrolysis and laboratory study of bioethanol derived therefrom [1]. However, [2], reported the use of percolation reactor in an integrated biorefinery using a dried distillers' grains with an achievement of high pentose yield in a liquid re-circulation process. This research work therefore explored the design of a percolation reactor in preference to others in view of its advantages at reducing acid consumption, promoting higher yield of hemicellulose sugars and lowering the yield of sugar degradation products [3] [4]. Furthermore, unlike the batch and plug flow reactors, the designed percolation reactor does not require solid or liquid separation interface as the solid particles placed in the percolation baskets, do not flow with the liquid as in other reactors. Also, the temperature of the designed percolation reactor is monitored by a thermocouple and controlled by a temperature controller. Hence, the entire process is monitored and maintained at pre-set values. Therefore, damages due to particle attrition are minimal in this reactor as compared to other types of reactors.

The percolation reactor is a packed-bed flow-through reactor. This reactor is tubular and it is filled with solid catalyst particles, most often used to catalyse gas reactions. The chemical reaction takes place on the surface of the catalyst. The advantage of using a packed bed reactor is the higher conversion per weight of catalyst than other catalytic reactors. There are certain advantages in this reactor in comparison to batch and plug flow reactors for hydrolysis of lignocellulosic materials. Lower sugar decomposition can result, since the sugar product is removed immediately after formation in this reactor. A high concentration of sugar can be produced by using a percolation reactor, since a high solid/liquid ratio can be used and also mass transfer between the liquid medium and solid catalyst is facilitated at high liquid flow rate. Furthermore, unlike the batch and plug flow reactors, this process does not need a solid or liquid separation [4] as the solid are placed in the percolation baskets and do not flow with the liquid. Damages due to particle attrition are minimal in this reactor when compared to

other types of reactor. In a study by the National Renewable Energy Laboratory (NREL) in the USA, a continuously flowing, two-stage percolation reactor resulted in more than 95% of the theoretical yield of solubilized xylose sugars (monomeric and oligomeric) from yellow poplar sawdust [5]. Percolation reactors were used in most of the old wood sugar processes such as the Scholler process, the Madison wood sugar process, and some of the Soviet processes [4].

2. Materials and Methods

The percolation reactor **Figure 1** consists of two concentric cylinders made from 3 mm galvanised steel plate. The inner cylinder has a diameter and a height of 270 mm and 456 mm respectively, while the outer cylinder has a diameter of 370 mm and height of 456 mm. Mild steel was selected for the design because it is available, cheap, corrosion resistant and could withstand high temperature. A 50 mm thick fibreglass was used as a lagging material and sandwiched between the two cylinders to prevent heat loss and gain in the reactor chamber. A discharge outlet is incorporated into the reactor for the collection of hydrolysed sugar at various predetermined intervals. The base of the reactor chamber is made conical in shape for easy discharge of hydrolyzate after hydrolysis and cleaning after use.

The perforated basket holding the feedstock in the reactor for hydrolysis has a mesh size of 297 microns and sits directly inside the inner cylinder. However, it could be moved or put in place as required through installed handles. A heating compartment through which the hydrolyzate circulates is attached to the reactor and powered by a 3000 W heating element. The temperature of the component is controlled and regulated by a type-K thermocouple and a temperature controller

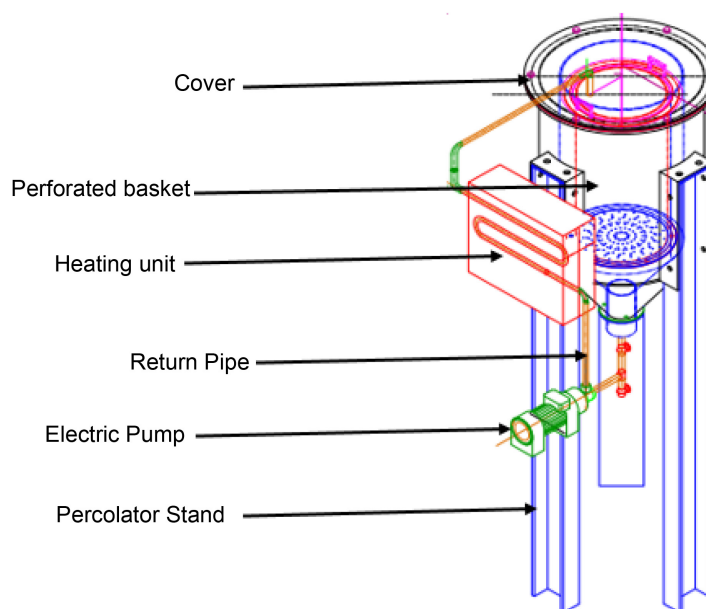


Figure 1. Percolation reactor with liquid recirculation used for biomass hydrolysis.

at desired set points. The rate of hydrolyzate circulation and pressure is controlled by a variable speed pump of 1.83 W capacity. A control box that superintends and monitors the entire operation of the percolation reactor is designed and incorporated into the reactor. The reactor operates by receiving materials into the hydrolysis basket, generate hydrolyzates by circulating heated water with dilute acids at pre-set temperature, pressure and constant flowrate. Heat supply to the reactor is reliable and rapid while heat loss is very minimal.

3. Design Considerations for the Percolation Reactor

The following design considerations influenced the design of the percolation reactor for the acid hydrolysis of lignocellulosic biomass wastes.

3.1. Volume of Reactor Chamber (V_i)

The volume of the reaction chamber was determined to be 0.026 m³ (26 ltrs) using Equation (1) as proposed by [6]. The reactor chamber is the inner component of the machine where the homogenization of reactant takes place.

$$V_i = \frac{\pi}{4} D_i^2 l_i \quad (1)$$

where:

V_i is the reactor volume;

D_i is the inner diameter of the reactor;

l_i is the internal length of the reactor.

3.2. Volume of Reactor's Perforated Basket

The perforated basket was determined to be 0.0093 m³ (9.3 ltrs) using Equation (2) suggested by [6]

$$V_b = \frac{\pi}{4} D_b^2 l_b \quad (2)$$

where:

V_b is the perforated basket volume;

D_b is the diameter of the perforated basket;

l_b is the depth of perforated basket.

3.3. Volume of Feedstock Required for Hydrolysis with a Known Mass of Feedstock

The volume of feedstock mixture (V_m) charged into the reactor was determined to be 0.0053 m³ (5.3 ltrs) using Equation (3).

$$V_m = \text{Volume of biomass} + \text{Volume of water} \quad (3)$$

$$\text{Volume of substance}(V_m) = \frac{\text{Mass of Substance}}{\text{Density of Substance}} \quad (4)$$

3.4. Heat Gained by Water to Change Phase from Liquid to Vapour

Heat gained by water to change phase = ml_v

where:

m is the mass of water;

l_v is the specific latent heat of vapourization;

$$\text{Heat gained by biomass} = m_C C_{p_C} \Delta t + m_W C_{p_W} \Delta t \quad (5)$$

where:

m_C is the mass biomass;

C_{p_C} is the specific heat capacity of biomass;

Δt is the change in temperature;

C_{p_W} is the specific heat capacity of water;

Total heat gain = heat gained by water to change phase + heat gained by biomass;

Total heat gained = heat supplied by the heating element;

$$\text{Heat supplied by heating element} = P_h t \quad (6)$$

P_h is the power rating of the heating element;

t is the time in seconds.

According to heater selection and sizing (BTU Electric Heater, 2US) for 220 V applied voltage, the efficiency of heater voltage is 84%.

$$\text{Actual rating of heating element} = \frac{\text{Theoretical Power}(P_h)}{\text{Efficiency of heater voltage}} \quad (7)$$

The actual heat generated by the heating element in 25 minutes is given below

$$\text{Actual heat generated}(Q_W) = IVt = P_h t \quad (8)$$

3.5. Determination of Thickness and Type of Insulation

In order to avoid or reduce heat losses from the mixing chamber through the walls of the reactor from the basket to the inner shell and to the outer shell of the reactor, it is necessary to insulate the vessel with properly selected and sized material. The insulating material was fibre glass, and the choice of fibre glass is that it has high thermal resistivity and it is readily available. Applying Fourier's Equation of heat transfer through conduction,

$$Q = -\frac{\theta_1 - \theta_2}{\frac{x_1}{k_1 A_1} + \frac{x_2}{k_2 A_2}} \quad (9)$$

where:

Q is the calculated rating of the heating element;

θ_1 is the temperature of inner shell of the reactor;

θ_2 is the temperature of the outer wall of the reactor;

k_1 is the heat transfer coefficient of steel;

k_2 is the heat transfer coefficient of fibre glass;

A_1 is the area of steel plate;

A_2 is the area to be filled by fibre glass;

x_1 is the thickness of steel plate;

x_2 is the thickness of glass wool.

$$x_2 = -k_2 A_2 \left(\frac{\theta_1 - \theta_2}{Q} - \frac{2x_1}{k_1 A_1} \right) \quad (10)$$

$$A = 2\pi r h \quad (11)$$

$$A_1 = 2\pi r_1 h$$

where:

r_1 is the radius of inner shell of the bioreactor;

h is the height of the reactor from the heat source to the top cover of the vessel.

$$A_2 = 2\pi r_2 h$$

where:

r_2 is the radius of shell to be filled with fibre glass;

h is the height of the reactor from the heat source to the top cover of the vessel.

$$\text{Thickness of insulator } x_2 = -k_2 A_2 \left(\frac{\theta_1 - \theta_2}{Q} - \frac{2x_1}{k_1 A_1} \right) \quad (12)$$

The unit is divided into two (inner chamber and out chamber) with the space between filled with the lagging materials (fibre glass), the purpose of lagging material is to reduce heat losses to the minimum level. Fibre glass was considered for the lagging material because it is a poor conductor of heat insulation.

3.6. Heat Transfer in the Reactor Chamber

The heat transfer in the reactor chamber is by convection and conduction. Heat is transfer by convection from the cassava peels to the basket, from basket to the inner wall of the reactor chamber, heat transfer is by conduction from inner wall of the reactor chamber to the insulating material and from the insulating material to the outside wall of the reactor and convective heat transfer from the outside wall of the reactor to the surrounding.

Heat transfer from cassava peels at temperature T_c to the wall of the reactor basket at temperature T_{w1} is given in Equation (13)

$$Q = hA(T_c - T_{w1}) \quad (13)$$

Heat transfer from the basket of the reactor at (T_{w1}) to the inner material of the reactor at (T_{w2}) is given in Equation (14)

$$Q = \frac{2\pi K_m L (T_{w1} - T_{w2})}{\ln \frac{r_2}{r_1}} \quad [7] \quad (14)$$

Heat transfer from inner material at (T_{w2}) to the insulating at (T_{w3}) is given in Equation (15)

$$Q = \frac{2\pi K_f L (T_{w2} - T_{w3})}{\ln \frac{r_3}{r_2}} \quad [7] \quad (15)$$

Heat transfer through the insulating material to the outside wall of the reactor cylinder of thickness t_3 is given in Equation (16)

$$Q = \frac{2\pi K_m l (T_{w3} - T_{w4})}{\ln \frac{r_4}{r_3}} \quad [7] \quad (16)$$

Heat transfer from the outside wall of the reactor to the surrounding atmosphere is given in Equation (17)

$$Q = hA(T_{w4} - T_\infty) \quad [7] \quad (17)$$

Combining Equations (13)-(17),

$$Q = \frac{2\pi L(T_c - T_\infty)}{\frac{1}{r_1 h_c} + \frac{\ln(r_2/r_1)}{K_g} + \frac{\ln(r_3/r_2)}{K_f} + \frac{\ln(r_4/r_3)}{K_m} + \frac{1}{r_4 h_a}} \quad (18)$$

Since Q is known from Equation (18), then substitution into Equation (18) given the interface temperatures T_{w1} , T_{w2} , T_{w3} and T_{w4}

$$r_3 = r_2 + 2t_2$$

$$r_4 = r_3 + 2t_3$$

where:

Q is the heat transferred in the reactor chamber to the surrounding (kJ/kg);

l is the length of the reactor cylinder;

h_a is the convective heat transfer coefficient of air;

h_c is the convective heat transfer coefficient of biomass;

K_g and K_m is the thermal conductivity of galvanised plates and mild steel;

K_f is the thermal conductivity fiberglass;

A is the surface area of the reactor cylinder;

t_1 is the thickness of the perforated basket;

t_2 is the thickness of the inner cylinder;

t_3 is the thickness of the fiberglass;

T_∞ is the ambient temperature;

T_c is maximum temperature of the biomass in the reactor.

3.7. Pressure in the Bioreactor (P_R)

During the mixture of feedstock within the reactor, pressure is created as a result of the heat generated from the heater which leads to collision of water molecules and the feedstock which built up the pressure with the wall of the reactor chamber. The estimated pressure was calculated using Equation (19)

$$P_R = \frac{F}{A_i} \quad [6] \quad (19)$$

where:

P_R is the pressure in the bioreactor;

A_i is the internal diameter of the reactor;

F is the force.

3.8. Increase in Diameter (ΔD_i) Due to Internal Pressure

The increase in internal diameter of the reactor shell due to the internal pressure produced was determined using given Equation (20)

$$\Delta D_i = \frac{P_R D_i}{2 t_i E} \left(1 - \frac{\mu}{2} \right) \quad [6] \quad (20)$$

where,

P_R is the internal pressure produced in the reactor;

t_i is the thickness of plate;

E is the Young modulus of the shell material;

μ is the poisson ratio of the material ranging.

3.9. Increase in Length (Δl_i) Due to Internal Pressure

The increase in length of the reactor shell due to the internal pressure produced was calculated using given Equation (21)

$$\Delta l_i = \frac{P_R l_i D_i}{2 t_i E} \left(\frac{1}{2} - \mu \right) \quad [6] \quad (21)$$

where,

P_R is the internal pressure produced in the reactor;

t_i is the thickness of plate;

E is the Young modulus of the shell material;

μ is the poisson ratio of the material ranging;

l_i is the length of the inner cylinder.

3.10. Increase in Internal Volume (ΔV_i) Due to Internal Pressure

The increase in internal volume $\Delta V_i = \frac{\pi}{4} (D_i + \Delta D_i) (l_i + \Delta l_i) - \frac{\pi}{4} D_i^2 l_i$ (22)

3.11. Pump Design

Density of water mixture is calculated as:

$$\rho_w V_w + \rho_c V_c = \rho_m V_m \quad (23)$$

$$\rho_m = \frac{\rho_w v_w + \rho_c v_c}{v_m} \quad (24)$$

The total Power exerted to the mixture at a height of 0.456 m is:

$$P_m = \rho_m g Q H \quad (25)$$

$$\text{Flow rate} = Q = \frac{V_i}{60 \text{ s}}$$

3.12. Pipe Sizing

The pipe used for the piping of the hydrolyzate from the top of the reactor down to the pump to the heater was made galvanized and they were selected according to ASTM standard to accommodate fouling.

4. Results and Discussion

The wall of the reactor and its height were determined to have increased slightly by 3.022×10^{-9} m and 1.201×10^{-9} m respectively, while the change in volume was found to be 8.8×10^{-9} m³. However, the operating temperature and the internal pressure of the circulating hydrolyzate, were largely responsible for the infinitesimal dimensional changes, which the reactor shell could withstand without undue material stress. The results for the design of the percolation reactor are presented in **Appendix A** and the percolation efficiency was estimated for the hydrolysis of biomass such as cassava peelings using Equation (26);

$$\text{Percolation Efficiency for hydrolysis of cassava peelings} = \frac{\text{output}}{\text{input}} \times 100\% \quad (26)$$

Input is the total mass of biomass and acid solution needed for hydrolysis = 2.5 kg.

Output is the mass of cassava peeling hydrolysed = 1.61 kg.

$$\text{Percolation efficiency for hydrolysis} = \frac{1.61}{2.5} \times 100\%.$$

Percolation Efficiency for hydrolysis = 64.4%.

The percentage efficiency of the percolation reactor for the hydrolysis of cassava peels indicates that the reactor was able to completely hydrolyse the biomass feedstock into simple sugars.

1) Assembly of the Percolation Reactor (**Figure 2**).

2) Developed Reactor.

The reactor was assembled and placed on a flat surface as shown in **Figure 3**.

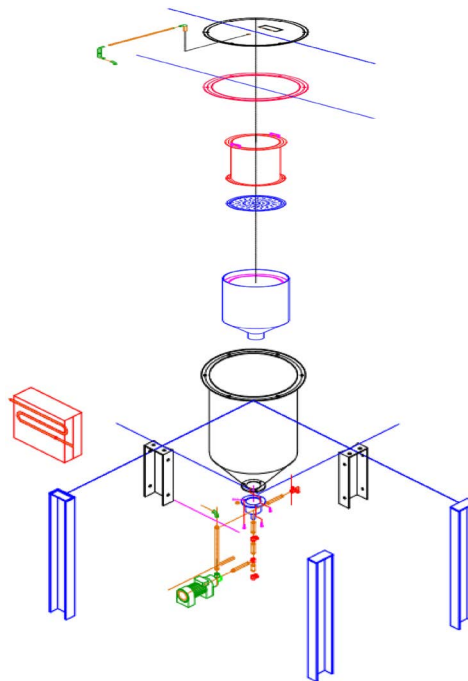


Figure 2. Assembly of the reactor parts.



Figure 3. The percolation reactor.

5. Conclusion

The percolation reactor was designed and fabricated using locally available materials, while the hydrolysis of lignocellulosic biomass was carried out on it, using cassava peels as feedstock. The efficiency of the percolation reactor for the hydrolysis of cassava peels was estimated to be 64.4% indicating that the reactor was able to completely hydrolyse the biomass feedstock. The reactor is simple to operate, easy to maintain and affordable.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix A: Design Parameters for the Design Percolation Reactor

| S/N | DESIGNS | EQ. USED | RESULT |
|-----|---|--|---------------------------------------|
| 1 | Volume of the Reactor chamber | $\frac{\pi}{4} D_i^2 l_i$ | 0.0261 m ³ (26 Litres) |
| 2 | Volume of the perforated basket | $\frac{\pi}{4} D_b^2 l_b$ | 0.0093 m ³ (9.3 Litres) |
| 3 | Volume of feedstock required for hydrolysis | $V_c + V_w$ | 0.0053 m ³ (5.3 Litres) |
| 4 | Determination of Green basis of the cassava peels | $\frac{W_c - D_c}{D_c} \times 100\%$ | 60% |
| 5 | Heat gained by water to change phase | ml_v | 2.256×10^6 J/kg |
| 6 | Heat gained by cassava peels | $M_c C p_c \Delta t + M_w C p_w \Delta t$ | 2841.305 kJ |
| 7 | Heating element rating | $\frac{\text{Theoretical Power}}{\text{Efficiency of heater volatge}}$ | 3.1777 kW |
| 8 | Actual heat generated | $(Q_w) = IVt = P_h t$ | 4500 kJ |
| 9 | Determination of thickness and type of insulation | $-k_2 A_2 \left(\frac{\theta_1 - \theta_2}{Q} - \frac{2x_1}{k_1 A_1} \right)$ | 100 mm |
| 10 | Heat transfer in the reactor chamber | $\frac{2\pi l(T_c - T_\infty)}{\frac{1}{h_c A} + \frac{r_1}{K_g} + \frac{\ln \frac{r_2}{r_1}}{K_f} + \frac{\ln \frac{r_4}{r_3}}{K_m} + \frac{1}{h_a A}}$ | 0.434 kJ/kg |
| 11 | Pressure in the reactor chamber | $\frac{F}{A_i}$ | 38.04 N/m ² |
| 12 | Increase in diameter due to internal pressure | $\frac{P_r D_i}{2t_i E} \left(1 - \frac{\mu}{2} \right)$ | 3.022×10^{-9} m |
| 13 | Increase in length due to internal pressure | $\frac{P_r l_i D_i}{2t_i E} \left(\frac{1}{2} - \mu \right)$ | 1.201×10^{-9} m |
| 14 | Increase in volume due to internal pressure | $\frac{\pi}{4} (D_i + \Delta D_i)(l_i + \Delta l_i) - \frac{\pi}{4} D_i^2 l_i$ | 8.8×10^{-9} m ³ |
| 15 | Determination of pump size | $\rho_m g Q H$ | 0.5 hp |
| 16 | Pipe sizing | Selected according to ASTM standard | 1 and $1\frac{1}{2}$ inch |