

Development of a laboratory scale biodiesel batch reactor

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Abstract - The use of biodiesel as an alternative fuel, either neatly or in blends with conventional diesel, in internal combustion engine has been widely adopted worldwide. However, the high cost of procuring basic equipment and facilities to produce biodiesel on a small scale hinders its sustainable production. In this study, a laboratory scale biodiesel reactor was designed and fabricated using locally available materials. Experiments were conducted at 6:1 molar ratio of alcohol to refined cooking oil, operational temperature of 62°C, and 421rpm stirrer speed with the machine loaded to 5/12 of its capacity to ascertain the performance of the reactor. Samples of the produced biodiesel were collected at 10minutes interval for a residence period of 90minutes. The results showed that the maximum yield was obtained after 20minutes residence time. Also, the properties of the biodiesel produced at this residence time were like that obtained at higher residence time and that of EN14214 biodiesel standard. Although we recommend that a proper evaluation should be carried out (our next work) and there's a need for a methanol recovery unit.

Key Words: renewable energy, biodiesel reactor, transesterification, waste vegetable oil, methyl ester.

1. INTRODUCTION

Over the years, the actions of human beings have altered the world balances which are mainly due to the overwhelming effects of global civilization and industrialization. These imbalances have resulted into significant changes in the climatic conditions of the different regions of the world. The temperate region of the world is characterized with rise in sea level, flooding, hurricane and tornadoes; while the tropical region experiences incremental rise in temperature leading to drastic fall in sea level, water scarcity, famine and spread of diseases. This disturbing phenomenon is known as global warming [1].

Global warming is because of continuous emission of greenhouse gases – carbon dioxide, water vapor, and methane gas – into the atmosphere, which are produced majorly from the burning of fossil fuels both in domestic and industrial capacities. To abate this negative trend of global warming, attention has over the years been shifted to the production of clean and green energy (e.g. Biofuel) from renewable sources such as biomass, wind, rain, tides, waves, geothermal, solar, agricultural waste, municipal waste etc. Energy from a renewable source is termed renewable energy. Renewable energy is no threat to the environment, as its combustion produces significantly low or no greenhouse gases [3].

Major drawback to the production of biofuel arises from the stiff competition between the use of land for food production and renewable energy generation. Many critics have argued that production of biofuel from food crops (first generation biofuels) is not sustainable as it has put unnecessary strain on food production with consequent rise in food prices. This has necessitated the development of second generation biofuels that make use of non-edible crops and waste products. Second generation biofuels utilize sustainable feedstock and do not compete with food in the animal or human food chain, such as biodiesel from waste vegetable oil [6].

Biodiesel refers to a vegetable oil or animal fat-based fuel which contains a long chain alkyl ester obtained through the process known as transesterification. This process involves chemically reacting the vegetable oil or animal fat with an alcohol, usually ten-part oil to one-part alcohol, in the presence of catalyst such as NaOH and KOH. The alcohol used in this type of reaction is usually methanol or ethanol and it can be carried out through several methods as common batch process, supercritical process, ultrasonic method and microwave method [5].



The feedstock to produce biodiesel can be obtained from variety of oils such as vegetable oils, waste vegetable oils, animal fats, algae and oil from halophytes. However, the production of biodiesel from edible oils had been greatly condemned due to profound friction between food for consumption and fuel production which has led to rising price of vegetable oil in the developing world, giving way to increase poverty. Hence the use of non-edible oil, waste vegetable oil and oil obtained from waste materials has been greatly supported as a viable alternative for the massive and sustainable production of biodiesel [11].

[13] stated that five basic steps are involved in the production of biodiesel from waste vegetable oil, namely: oil pre - treatment, alcohol-catalyst mixing, transesterification, products separation, and purification of produced biodiesel.

The oil pre - treatment is essential to remove free fatty acid (FFA) that might impede the transesterification reaction [5]. [11] stated that the common recipe for transesterification is to combine 100parts of oil with 22 parts of alcohol and 0.5 - 1.0 parts of catalyst.

[5] noted that the separation process is based on the fact that biodiesel and glycerol are sparingly mutually soluble and that there is a significant difference in the density between the two. The separation can be carried out through decanter system, centrifuge system and hydroclone.

[13] affirmed that to purify the biodiesel a successive washing with water is required, since the contaminants are soluble in water. The first washing uses water and acid to neutralize the base catalyst, the other two washes make use of only water. Traces of water are then dried from the fuel.

According to [10], chemical reactions in a reactor, take place under controlled conditions and it is therefore essential to exercise substantial control in selecting reactor design variables to optimize the performance of the process and the quality of the product. These variables are: construction material, mode of operation, catalyst type, mixing pattern as well as the temperature, pressure and volume of the reactor

[7] in his experiment used a batch reactor which was equipped with a helical-ribbon like agitator. Experiments were conducted at 6:1 molar ratio of alcohol to refined soybean oil, operational temperature of 64 °C, KOH concentration of 1%wt oil, and three levels of agitation speed; 600, 750, and 900 rpm. The agitator design and its helicon movement led to a uniform phase formation of insoluble alcohol and oil in which about 97.3% conversion of triglycerides to methyl esters (biodiesel) was achieved.

A laboratory scale reactor is needed to enable researchers perform their experiments with very cheap equipment. Local farmers that also want to produce biodiesel on their farms also need one. There's also a need to eliminate the pump required for fluid transfer (saves cost) and have a reactor with separation and other units attached.

Hence, this study focused on the design and fabrication of a batch reactor equipped with helical – ribbon like agitator with separating unit for biodiesel production from waste vegetable oil.

2. MATERIALS AND METHODS

2.1 Description of the Reactor

The schematic illustration of the reactor is shown in fig 1. The reactor is made of a mild steel vessel of approximately twelve liters by volume, properly sealed to avoid loss of reactant. The reactants are stirred by a helical ribbon like agitator driven by a belt, pulley and gear system which is powered by an electric motor. The vessel is cylindrical from the top and conical towards the bottom. An oil heater is used to heat up the reactants in the vessel and it is connected to a thermocouple to regulate the temperature. A mild steel cone — shaped vessel with sight glass is placed at the bottom of the first vessel, this serves as the separating and purification vessel. It is mounted on a system of belt, pulley and gears to

make it possible for it to separate like a centrifuge to increase the rate of separation.

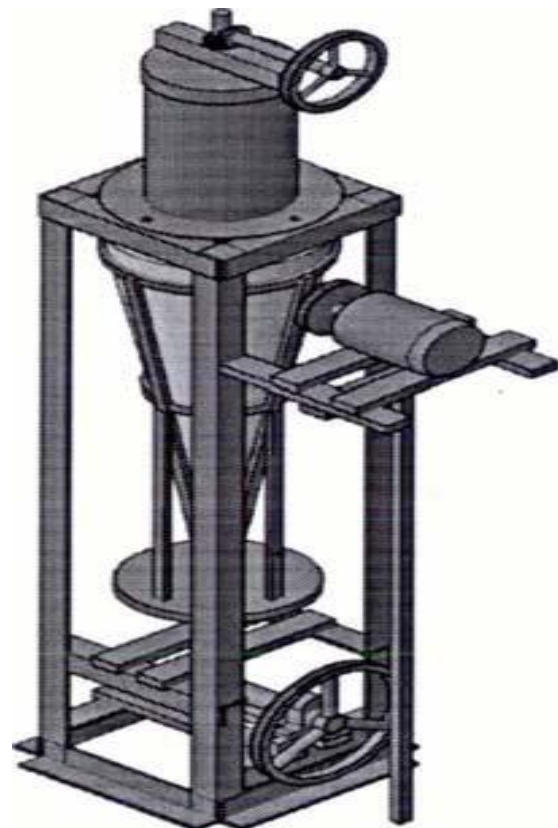
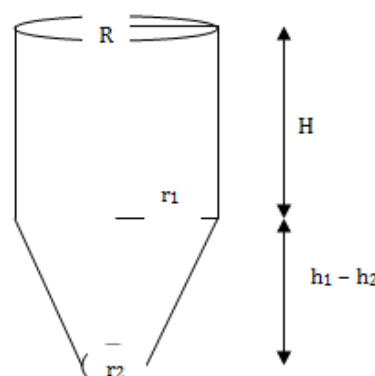


Figure 1: Isometric view of the reactor

2.2 Reactor's Components Design

2.2.1 Design of Reactor Vessel

The reactor vessel is the container that holds the reactant and it is fabricated using mild steel. It is cylindrical at the top and tapers towards the bottom to allow for easy discharge of the product. Reactor vessel capacity is obtained using the relationship given as: reactor capacity = volume of cylindrical section + volume of the frustum.



$$V = \pi R^2 H + \left(\pi \times \frac{1}{3} \right) (r_1^2 h_1 - r_2^2 h_2) \text{ equation 1.}$$

Where: $R = 100\text{mm}$, $H = 350\text{mm}$, $r_1 =$, $r_2 =$ and $h_1 - h_2 = 100\text{mm}$. Hence, $V = 12$ litres.

2.2.2 Design of Separation Unit

This is a conical shaped unit placed on a rotating mechanism thus acts like a separating funnel as well as a centrifuge. It is made up of mild steel with sight glass to check the extent of separation. It has a total volume that is two times the volume of the reactor so as to accommodate the washing water.

$$V = \frac{\pi}{3} (r^2 \times h) \quad \text{equation 2}$$

Where: $r = 150\text{mm}$, $h = 850\text{mm}$. Hence, $V = 20$ liters.

2.2.3 Design of Separation Unit

Heat energy is essential in transesterification reactions as it increases the rate of reaction and conversion of the feedstocks into biodiesel which depend on temperature variation. The rate of reaction increases as the temperature increases up to a temperature of 60°C but beyond this the rate of reaction tend to be uniform, the heat energy is thus provided to heat the feedstocks to the desired constant temperature that will provide maximum rate of reaction. The capacity of the heating element is obtained using:

$$Q = M_o C_o (T_s - T_r) \quad \text{eq. 3}$$

And, heater electric power:

$$P_H = \frac{Q}{\text{delivery time (sec)}} \quad \text{eq. 4}$$

C_o (oil specific heat capacity) = 5 KJ/KgK , M_o (mass of oil) = 13Kg , T_s (operating temperature) = 60°C , T_r (operating temperature) = 25°C and the delivery time is 10 minutes.

Hence, $Q = 2275\text{KJ}$ and $P_H = 4000\text{watts}$

2.2.4 Electric Motor Requirement

The power required to operate the reactor is a function of the power needed to drive the stirrer (P_{st}) and the separation unit (P_s). The power to rotate the stirrer (P_{st}) is related to fluid density, fluid viscosity, rotational speed, and impeller diameter. The total power required to operate the reactor is given as $P_T = P_{st} + P_s$ equation 5

$$P_T = N_p \rho N^3 D_a^5 \quad \text{eq.6}$$

Where: N_p is power number which is gotten from plots of N_p versus N_{Re} (assuming N_p is 50), ρ is 1300kg/m^3 . N (impeller speed) = 15 rev/sec , D_a (impeller diameter) = 0.10m .

Hence, $P_{st} = 2193.75\text{watts}$

Assuming 80% transmission efficiency and using $1h_p = 0.75\text{KW}$.

$$P_{st} = 3.6 h_p$$

$$P_s = F (\text{force}) \times V (\text{velocity})$$

Also, $F = \text{mass} \times \text{acceleration due to gravity}$

And $V = \omega r$, $\omega = \text{angular velocity} = 63 \text{ rad/sec}$ and $r = 0.15\text{m}$.

Hence, $P_s = 2410.32 \text{ watts}$

Assuming 80% transmission efficiency and using $1h_p = 0.75\text{KW}$.

$$P_{st} = 4 h_p$$

2.2.5 Belt and Pulley Design

A 4hp electric motor with speed of 1400rpm is selected. A V-belt type is chosen for its compactness as a result of the short distance between the pulleys, and because of its positive drive (slip is negligible). Belt characteristics were selected based on Indian standard (IS2494 — 1974).

The pulley diameter of the stirrer was calculated using:

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} \quad \text{equation 7}$$

Where: N_1 is the driving pulley speed (1400rpm), d_1 is the driving pulley (125mm), while N_2 is the stirrer speed (900rpm).

Hence, $d_2 = 190\text{mm}$.

Also, the pulley diameter for the separation vessel was calculated using:

$$\frac{N_1}{N_3} = \frac{d_3}{d_1} \quad \text{equation 8}$$

Where: N_3 is the separation vessel speed (600rpm).

Hence, $d_3 = 290\text{mm}$.

The length of belt connecting pinion shaft pulley of the stirrer and the electric motor (L) is obtained using:

$$L = \pi (r_{p2} + r_{p1}) + 2C + \frac{(r_{p2} - r_{p1})^2}{C} \quad \text{eq. 9}$$

$C =$ center distance between the two pulleys (600mm), $r_{p1} =$ radius of the driving pulley (62.5mm) and $r_{p2} =$ radius of the driven pulley (95mm).

Hence, $L = 1697\text{mm}$

Also, the length of belt connecting pinion shaft pulley of the separator and the electric motor (L_s) is obtained using:

$$L_s = \pi (r_{p3} + r_{p1}) + 2C + \frac{(r_{p3} - r_{p1})^2}{C} \quad \text{eq. 10}$$

$C =$ center distance between the two pulleys (1067mm), $r_{p1} =$ radius of the driving pulley (62.5mm) and $r_{p2} =$ radius of the driven pulley (145mm).

Hence, $L_s = 2792\text{mm}$

2.2.6 Mitre Gears Design

The mitre gears were using the equations below based on the assumption that pitch angle (Op) = 45° .

Outside cone diameter:

$$D = D_p + 2a \cos 0_p = 53.54 \text{mm.}$$

Inside cone diameter:

$$D_d = D_p - 2a \cos 0_p = 46.46 \text{mm.}$$

$$\text{Cone distance} = D_p / 2 \sin 0_p = 35.35 \text{mm.}$$

2.2.7 Design of the Stirrer Shaft

The diameter of the stirrer shaft was determined by using the two equations below:

$$Z_p = \frac{\sqrt{(K_m M_R)^2 + (K_t T_R)^2}}{T_{max}} \quad \text{eq. 11}$$

$$Z_p = \frac{\pi d^3}{16} \quad \text{eq. 12}$$

Where: T_R is the torque developed in the shaft, M_R is the maximum bending moment, K_m and K_t are constants chosen to be 2.0, T_{max} is the maximum shear stress developed in the shaft (500.4Nm). Z_p = equivalent bending moment (120.89Nm), d is the shaft diameter.

Hence, d is equal to 40mm adjusted to accommodate extra load for safety reasons.

2.2.8 Design of the Separator Shaft

The diameter of the separator shaft was determined by using the two equations below:

$$Z_p = \frac{\sqrt{(K_m M_R)^2 + (K_t T_R)^2}}{T_{max}} \quad \text{eq. 13}$$

$$Z_p = \frac{\pi d^3}{16} \quad \text{eq. 14}$$

Where: T_R is the torque developed in the shaft, M_R is the maximum bending moment, K_m and K_t are constants chosen to be 2.0, T_{max} is the maximum shear stress developed in the shaft (176.54Nm). Z_p = equivalent bending moment (162.64Nm), d is the shaft diameter.

Hence, d is equal to 30mm adjusted to accommodate extra load for safety reasons.

2.3 Machine Fabrication

The components of the reactor were fabricated and assembled based on the design specifications as shown in table 1. The isometric view of the reactor is also shown in figure 1.

Table 1: Design summary

S/N	components	size	unit
1	Reaction vessel	12	L
2	Separation unit	20	L
3	Power to rotate stirrer	3.6	Hp
4	Separation unit power	4.0	Hp

5	Belt 1	1770	mm
6	Belt 2	2888	mm
7	Pinion shaft diameter 1	24	mm
8	Pinion shaft diameter 2	40	mm
9	Bevel shaft diameter	30	mm
10	Heater	4000	watt

2.4 Performance Evaluation of the Reactor

Biodiesel was produced from the reactor by transesterifying waste cooking oil with methanol at 6:1 molar, operational temperature of 62°C, and 421rpm stirrer speed with the machine loaded to 5/12 of its capacity for a total residence period of 90 minutes. The waste cooking oil was pretreated by removing its constituent solid particles and also heated to 100°C to remove traces of water. The biodiesel was recovered from the product by decantation.

The performance evaluation of the reactor was achieved by determining the biodiesel yields at various residence time at ten minutes' interval, in order to have the idea of the optimum biodiesel production time for future use of the reactor. Biodiesel was also manually produced using available local facility to serve as control. An A25591DDM2911 automatic density meter was used to determine the properties of the fuels.

Biodiesel yield was estimated, according to [5] & [7], using:

$$\% \text{ yield} = \frac{\text{volume of produced biodiesel}}{\text{volume of oil used}} \quad \text{equation 15}$$

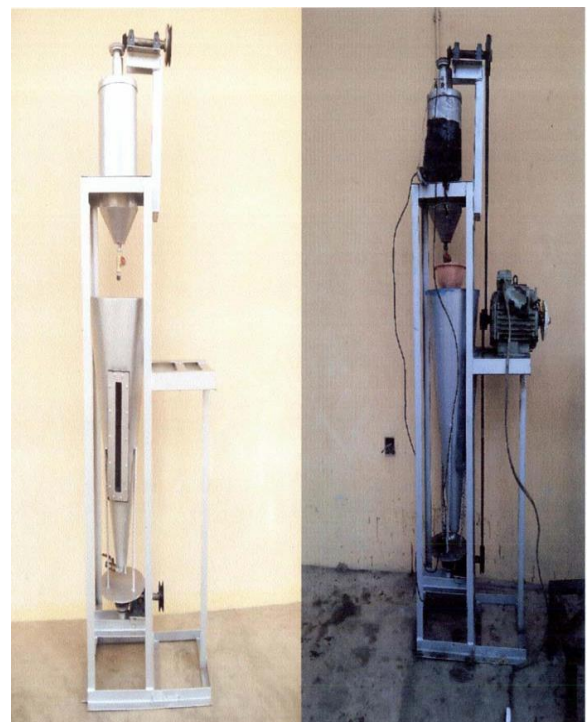


Figure 2: The reactor

3. RESULT AND DISCUSSION OF THE PERFORMANCE EVALUATION OF THE REACTOR.

Tables 2 and 3 present the results of the performance evaluation of the biodiesel reactor. Table 1 showed that at 10minutes residence time the yield was very low (9.53%), however at 20minutes residence time the yield increased a lot compared to at 10minutes (about six times). This quantity seems to remain approximately the same for the samples at residence time of 30minute and 40minute and this is consistent with the work of [5], though the highest yield was at 40minute. At the remaining residence time there was no consistent biodiesel yield variation, this could be due to the method adopted in the experiment; reduction in the reactant volume which serves as basis for yield determination.

Table 2: Biodiesel yield

S/N	Residence time (min)	% biodiesel yield
1	10	9.53
2	20	59.98
3	30	59.98
4	40	62.20
5	50	20.52
6	60	50.00
7	70	44.43
8	80	19.03
9	90	53.35
10	manual	98.00

Table 2 showed that all the biodiesel samples have specific gravity that are in the range of specific gravity for conventional diesel and this is consistent with the work of [7] and [8].

The manually produced biodiesel has only two phases as compared to the three phases of the machine produced one, this is because of efficient mixing that was achieved with the manual process. Also, its yield is high while its density is low when compared with the biodiesel produced from the reactor.

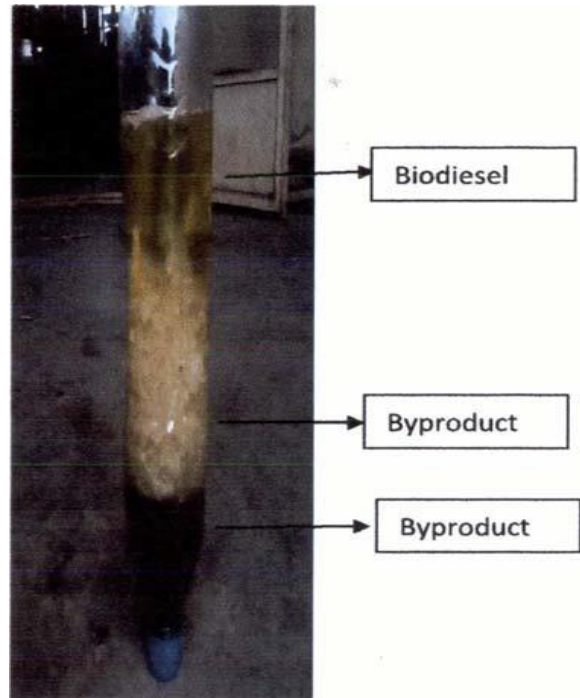


Figure 4: Biodiesel produced at 40 minutes' residence time.



Figure 5: Manually produced biodiesel.

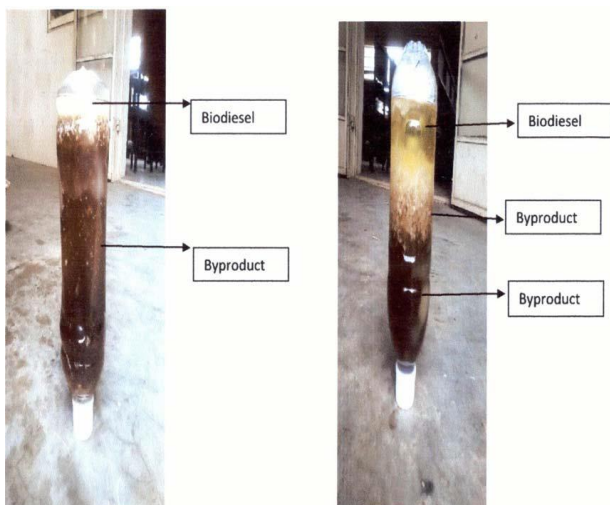


Figure 3: Biodiesel produced at 10 and 20 minutes' residence time.

Table 3: Characteristics of the biodiesel produced.

Name	Density(g/cm ³)	API gravity g 60F	API gravity g 15°C	API density g 60F	API density g 15°C	Specific gravity (V.C)	Apparent density(g/cm ³)	Specific gravity	Ethanol content(% volg ²⁰ °C)
10min									
20min	0.87564	29.37	29.31	0.8788	0.8791	0.8772	0.87453	0.8773	26.30
30min	0.87338	29.78	29.72	0.8765	0.8769	0.8750	0.87231	0.8750	25.53
40min	0.87450	29.57	29.52	0.8776	0.8780	0.8754	0.87270	0.8755	25.50
50mins	0.87313	29.83	29.77	0.8762	0.8766	0.8742	0.87152	0.8748	25.21
60mins	0.87318	29.82	29.76	0.8763	0.8767	0.8748	0.87215	0.8748	25.21
70mins	0.87310	29.83	29.77	0.8762	0.8766	0.8746	0.87193	0.8747	25.18
80mins	0.81889	40.45	40.38	0.8221	0.8225	0.8220	0.82070	0.8220	6.90
90mins	0.87425	29.62	29.56	0.8774	0.8778	0.8759	0.87325	0.8759	25.64
Petro diesel	0.85592	33.05	32.99	0.8591	0.8594	0.8574	0.85476	0.8574	18.84
Manual	0.86515	31.31	31.25	0.8683	0.8687	0.8667	0.86409	0.8668	22.98

4. CONCLUSIONS

From this study, the optimum residence time for the production of biodiesel from waste cooking oil and methanol is 20 minutes. The biodiesel produced from this reactor separated into three phases; biodiesel, and two different byproducts (possibly glycerol and soap) while two phases were observed from the manual biodiesel production (biodiesel and byproduct). Possible reasons for this include: low RPM of the stirrer which result in less agitation of the reactants (since 900rpm is the optimum for the reaction to occur) and low quality mild steel used which may be reacting with some of the reactants. We recommend that a proper performance evaluation be carried out and also a methanol recovery unit be added to make it truly the tool for researchers and small-scale farmers.

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