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Research Article

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Development of a Biodiesel Reactor

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Abstract The objective of this study is to develop a reactor for the production of biodiesel from palm-kernel oils (PKO). The base-catalysed transesterification reaction process is selected in the design of production process. In the transesterification reaction process, the PKO along with methanol and sodium hydroxide (NaOH) catalyst combine and reacted together to form the main product, biodiesel and by-product glycerol. The reactor consists of a cylindrical tank made of stainless steel. It has a water bath whereby the oil is heated with the use of a heating element. It also has a thermostat for the regulation of temperature. The reactor is then insulated with fibre glass preventing heat loss. The reactor is also equipped with stirrer for the agitation process and an electric motor which served as the prime mover. The reactor was fabricated and tested. The effects of temperature, time and methanol to oil ratio on the yield and quality of the biodiesel were determined. The average yield at temperatures of 40, 50, 60 and 70 ^oC were observed to be approximately 77.88, 80, 83.95, and 66.95% respectively. The average yield at methanol-oil ratios of 6:1, 9:1, 12:1 and 18:1 were observed to be approximately 83.95, 76.33, 73.12, and 72% respectively. The average yield at reaction time of 15 min, 30 min, 45 min and 60 min were observed to be approximately 82.59, 83.78, 83.94, and 83.95% respectively. The change in temperature, time and methanol-oil ratio has a significant difference on the yield at ($P \leq 5\%$). The highest yield of biodiesel obtained was 83.95%. The optimum conditions are reaction temperature of 60^oC, reaction time of 60 min and methanol-oil ratio of 6:1. The lowest biodiesel yield obtained was 65.32%. At room temperature, the specific gravity values obtained vary from 0.915 to 0.926 while the viscosity varies from 2.17mm^2/s to 3.32mm^2/s. The pour point values vary from 8ºC to 10ºC while the cloud point varies from 10ºC to 12ºC. The flash point varies from 64^oC to 102^oC. The biodiesel produced was tested for its quality and it was observed that their qualities measured up to ASTM standard specifications for biodiesel fuel.

Keywords Palm-kernel oil, Design, Transesterification, Biodiesel, Process

1. Introduction

Biodiesel is a renewable fuel that can be made from agricultural crops or other feedstock that are considered waste. It is an environmental friendly fuel that is sulphur free with less carbon monoxide, hydrocarbons, particulate matter and aromatic emissions and also has improved biodegradability, lubricity and reduced toxicity compared with petrol-diesel [1]. In today's world, petroleum is clearly the most important energy source, providing more than half the world's power, as well as being a basic material used in the manufacture of fertilizers, synthetic fibres, plastics, and synthetic rubber [2]. Biodiesel is an alternative fuel that is appropriate for use in unmodified, standard diesel engine [3]. It is typically produced by the reaction of vegetable oil or animal fat with alcohol such as methanol or ethanol in the presence of catalyst to yield mono-alkyl esters and glycerine. The equation of reaction for biodiesel production process is written below in Figure 1:

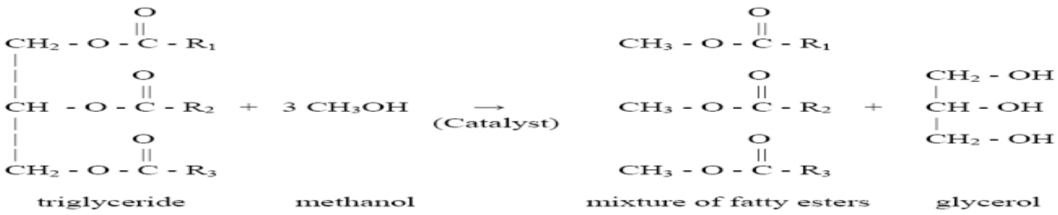

Figure 1: Equation of reaction for biodiesel production [4]

The diesel fuel used in diesel engines today is an environmental unfriendly fuel which leads to many environmental hazards, increase in green-house effect and also responsible for climate change. Therefore, there is a need for an alternative fuel that is environmental friendly and has similar fuel properties to conventional diesel fuel which can be used in existing unmodified diesel engines. There is also a need for low cost locally made biodiesel reactors instead of the imported ones which are too costly. However, there is a need to increase awareness of the use of biodiesel as an alternative fuel for diesel engines in Nigeria. As a result, it is very important to design a reactor for the production of biodiesel, fabricate and evaluate the performance of the reactor designed and also test the quality of the biodiesel produced.

In previous studies, two different mechanically agitated reactor vessels in mini scale size was developed and fabricated to produce biodiesel [5]. Esterification and transeterification routes were chosen as the production process. Both refined bleached deodorized (cooking oil) and used cooking oil were tested for the reliability of the reactor vessels and a biodiesel yield of above 90 % was obtained. Boopathi *et al.,* [6] also designed and fabricated a very simple and cost effective reactor for manufacturing biodiesel from fully recycled materials. The reactor fabricated can be effectively used in a home or a small hotel to manufacture biodiesel from recycled vegetable oil.

Commercial biodiesel production technologies can be grouped into three: base catalyzed transesterification with refined oils, base catalyzed transesterification with low free fatty acid greases and fats and acid esterification followed by transesterification of low or high free fatty acid greases and fats. Technologies can be run as batch or continuous processes but most U.S. firms have used batch technology. Base catalysis is much faster and has lower corrosion than acid catalysis and so, is most used commercially [7]. Base-catalyzed transesterification is affected by such variables as free fatty acids (FFA) and moisture contents, methanol-to-oil ratio, catalyst concentration, reaction temperature, and reaction time [8]. The reaction can be carried out at different temperatures, even at low temperatures such as 25ºC and 32ºC [9] but temperatures above 60ºC should be avoided since it accelerates the saponification of the glycerides by the alkaline catalyst before the completion of the transesterification [10]. Most processes for making biodiesel use a catalyst to initiate the esterification reaction. The catalyst is required because the alcohol is sparingly soluble in the oil phase. The catalyst promotes an increase in solubility to allow the reaction to proceed at a reasonable rate. In most studies for production of biodiesel with ethanol and methanolusing NaOH or KOH homogeneous catalysts, high yields of biodieselwere obtained within 1 hour of reaction time using one percent by weight catalyst concentration and between a 4:1 and 9:1 molar ratio of alcoholto oil. The catalyst usually requires a quantity equal to 1% of the oil quantity [11]. The transesterification reaction requires a low water (<0.06% w/w) and FFA content (<0.5% w/w) in the PKO. The literature indicates that the presence of water in the oil has a worse effect on transesterification than does the presence of FFA [12]. Once biodiesel is produced, this end product is nearly nontoxic and much less flammable than the alcohols, but more flammable than the starting oils.

2. Materials and Methods

2.1. Design Specifications and Equipment

The purpose of the study is to design an economically feasible reactor capable of producing biodiesel fuel from palm kernel oil. Therefore, the following design specifications were set:

i) Above 80% conversion into biodiesel should be achieved

ii) Compatible materials must be used in fabrication

iii) The production capacity of the reactor is 20L
iv) Maintaining the reaction temperature at 60ºC
v) Ideal mixing in the continuous stirrer reactor vessel must be achieved
vi) General safety of the process
vii) Simple in operation and low cost technology.

In this study, the base-catalysed transesterification reaction process was selected as the method used for the production of biodiesel. The palm-kernel oil (PKO) is considered to be the primary reactant. The transesterification reaction uses an alkali (NaOH) as catalyst and methanol is preferred to be the alcohol used. Methanol and sodium hydroxide (NaOH) are considered as alcohol and catalyst respectively because of their relatively low cost [7]. The PKO along with methanol and sodium hydroxide (NaOH) catalyst combine and react together to form the main product, biodiesel and by-product glycerol by means of transesterification reaction inside the reactor. The reactants entering the reaction vessel include the sodium hydroxide and methanol mixture and the PKO. The reactor comprises of the reaction vessel, stirrer, electric motor, heating element, thermostat, and insulation material. The material for the inner vessel and the stirrer is made of stainless steel because it is compatible to the chemical properties of the oil and glycerine. Galvanized steel is used for the outer vessel and a fibre glass is utilized as the insulation material preventing a heat loss. The transesterification reactor has a capacity of 20L and is equipped with a heating element where a thermostat is required to maintain a reaction temperature of 60°C. The reactor is clearly illustrated in Plate 1 below:

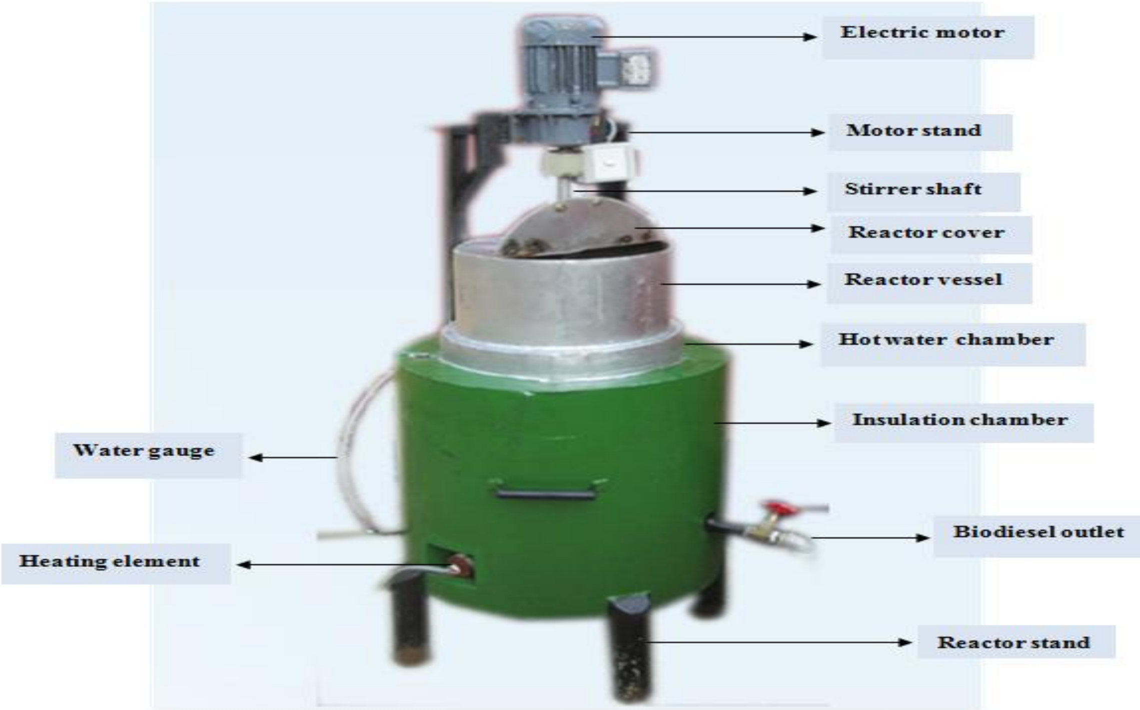

Plate 1: Fabricated reactor

The diameter and height of the reactor tank was determined using Equation 1 below;

$$D = \left(\frac{4V}{\pi R}\right)^{1/3} \qquad 1$$

where D = Diameter of the tank (m), V= Volume of the tank (m^3), Π = 3.142, and R = H/D factor i.e. ratio of height to diameter. For reactor tank, the height to diameter ratio was chosen as 2:1

The diameter of shaft was determined using the Equation 2below;

$$d^3 = \frac{16}{\pi S_s}\sqrt{(M_t k_t)^2 + (M_b k_b)^2} \qquad 2$$

Where$d$ = diameter of the shaft (mm), (M_b) = Maximum bending moment (Nm),
(M_t) = Torsional moment (Nm), K_b = combined shock = 1.5, Kt = fatigue factor = 1.0,

S_s= allowable shear stress = 55x10^{6}MN/m^2
The agitator power requirement was determined using the Equations 3, 4 and 5 below;

$$P = TW \quad (3)$$

$$T = \frac{\mu v}{r} \quad (4)$$

$$\omega = \frac{2\pi N}{60} \quad (5)$$

where P = Power (kW), T = Torque (Nm), μ = viscosity (m^2/s), ω = Angular velocity (rad/s), r = radius of the stirrer (m), v = volume of the stirrer (m^3), N = speed of the shaft (rev/min)
The heat energy requirement for the reactor was determined using the Equations6 and 7 below;

$$Q = C\Delta\theta + M_1C_1\Delta\theta + M_2C_2\Delta\theta \quad (6)$$

$$Power = \frac{Energy}{Time} \quad (7)$$

where Q = Heat energy (J), C = Heat capacity (JK^{-1}), C_1 = Specific heat capacity of water, (Jkg^{-1}K^{-1}), C_2 = Specific heat capacity of oil (Jkg^{-1}K^{-1}),$\Delta\theta$ = Change in temperature (°C) M_1 and M_2 = Masses of water and oil, respectively.

3. Results and Discussions

A reactor for the production of biodiesel from PKO was designed and fabricated using readily available and compatible materials. The reactor has also been tested. For the base-catalysed transesterification experiment conducted on the fabricated reactor, the effects of reaction temperature, methanol to oil ratio and reaction time on the biodiesel yield were determined. The optimization of the biodiesel yield was also determined to obtain the optimum conditions of the process parameters which gave the maximum yield.
For the variation of biodiesel yield with reaction temperature, the average biodiesel yield at temperatures of 40, 50, 60 and 70^{o}C at constant methanol to oil ratio of 6:1 were observed to be approximately 77.88, 80, 83.95, and 66.95% respectively. An increase in biodiesel yield with an increase in temperature was observed as shown in Figure 2below. There was a corresponding increase in the biodiesel yield at temperatures of 40^{o}C, 50^{o}C and 60^{o}C but at temperature of 70^{o}C, there was a decrease in the biodiesel yield.

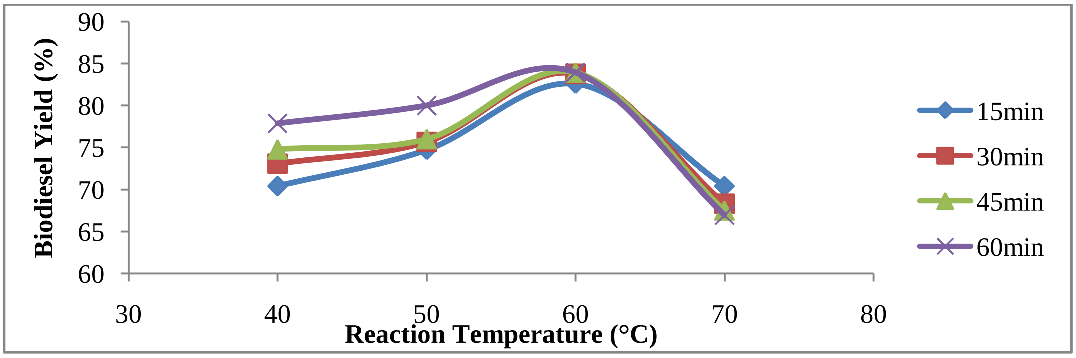

Figure 2: Variation of biodiesel yield with reaction temperature at constant methanol-oil ratio 6:1

For the variation of biodiesel yield with methanol-oil ratio, the average biodiesel yield at methanol-oil ratios of 6:1, 9:1, 12:1 and 18:1 at constant temperature of 60^{o}C were observed to be approximately 83.95, 76.33, 73.12, and 72% respectively. It was observed that the biodiesel yield decreased with an increase in methanol-oil ratio as shown in Figure 3 below.

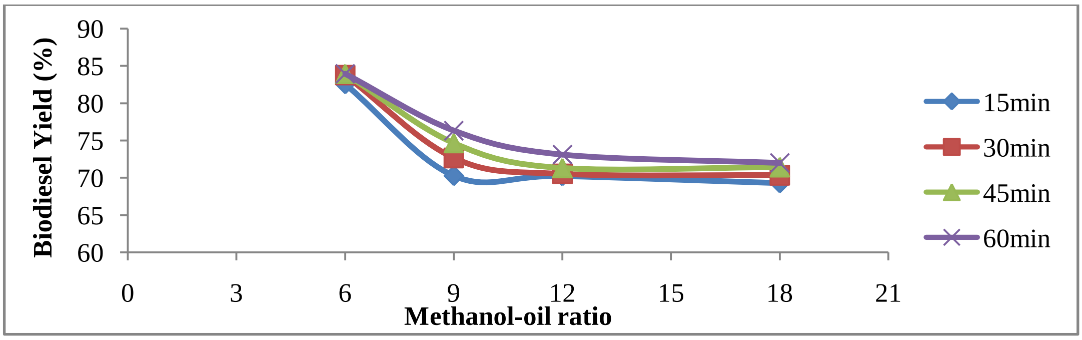

Figure 3: Variation of biodiesel yield with methanol-oil ratio at constant temperature of 60^{o}C

For the variation of biodiesel yield with time, the average biodiesel yield at reaction time of 15 min, 30 min, 45 min and 60 min at constant temperature of 60°C were observed to be approximately 82.59, 83.78, 83.94, and 83.95% respectively. An increase in biodiesel yield with an increase in time was observed as shown in Figure4 below. In the first 30 minutes, the reaction was slow due to the mixing of methanol with oil inside the reactor while the biodiesel yield increases rapidly at reaction time between 45 min to 60 min. However, excessive reaction time might leads to a reduction in the biodiesel yield due to the backward reaction, resulting in a loss of esters as well as causing more fatty acids to form soaps. The highest biodiesel yield of 83.95% was obtained at a reaction time of 60 min at constant temperature of 60°C.

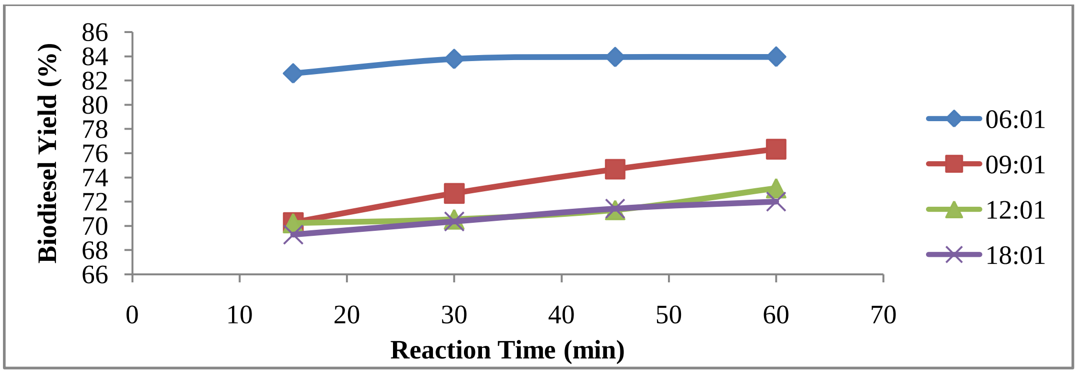

Figure 4: Variation of biodiesel yield with reaction time at constant temperature 60°C

The optimum values of methanol-to-oil molar ratio, reaction time and reaction temperature were found to be 6:1, 60min, and 60°C respectively, to achieve 83.95 % maximum biodiesel yield. However, the minimum values of methanol-to-oil molar ratio, reaction time and reaction temperature were found to be 18:1, 15min, and 40°C respectively, to achieve 65.32 % minimum biodiesel yield.

The quality and the physical characteristics of the biodiesel produced were determined using ASTM standard specifications. The Table 1 below shows the comparison of the results being tested and the standardvalues of biodiesel:

Table 1: Comparison of petroleum diesel and biodiesel fuels standards with the biodiesel produced

Fuel property	Petroleum diesel	Biodiesel	Biodiesel produced
Fuel standard	ASTM D 975	ASTM D 6751	
Viscosity at 40°C (mm^2/s)	1.3 - 4.1	1.9 – 6.0	2.17-3.32
Specific gravity at 60°F	0.85	0.86 – 0.90	0.915-0.926
Flash Point (°C)	60 - 80	100 - 170	64-102
Cloud Point (°C)	-15 to 5	-3 to 12	10-12
Pour point (°C)	-35 to -15	-15 to 10	8-10

Comparing the specific gravity values obtained for the biodiesel product with the ASTM D6751 standard specifications for biodiesel, it was observed that the specific gravity values are higher than the ASTM standard specifications for biodiesel. Specific gravity has been described as one of the most basic and most important properties of fuel because some important performance indicators such as cetane number and heating values are correlated with it [13-14]. It has also been reported to be connected with fuel storage and transportation [15-16]. At room temperature, the specific gravity values obtained for the biodiesel product vary from0.915to 0.926 while the ASTM D6751 standard specifications for biodiesel vary from 0.86 to 0.90. This high specific gravity values obtained might be as a result of the feedstock used. However, results obtained for viscosity measurement fall within the range of values acceptable for alternative diesel fuel. These results also agreed closely with a number of earlier works on other oil crops as well as series of alcohol-diesel blends. From the result presented, the viscosity of the biodiesel produced at different reaction conditions ranges from (2.17 to 3.32) which fall within the range prescribed by ASTM D6751 standard (1.9 – 6.0) mm^2/s for biodiesel. This implies that the biodiesel produced satisfies the fluidity requirement of an alternative biodiesel. From Table 1, it was observed that the pour point obtained for the biodiesel ranges from (8°C to 10°C) which fall within the range prescribed by ASTM D6751 standard (-15°C to 10°C) for biodiesel. It was also observed that the cloud point obtained for the biodiesel ranges from (10°C to 12°C) which were within a comparable range with previous results from several authors. Results obtained for flash point measurement ranges from (64 -102) °C which fall within the range of values acceptable for alternative diesel fuel.

4. Conclusion and Recommendations

Conclusion

A reactor for the transesterification process for biodiesel production from PKO has been successfully designed, fabricated and tested according to the design requirements and specifications. The total cost for fabricating the biodiesel reactor was estimated to be One Hundred and Twenty Thousand Naira. The biodiesel produced by the reactor gave some good results compared to the ASTM standard specification for biodiesel fuel. However, the specific gravity is still very high compared to the ASTM standard.

Recommendations

- **a.** For further research work, hydrocyclones should be designed and manufactured for the quick separation of the biodiesel fuel from the glycerol by-product.
- **b.** Biodiesel should be recommended as an alternative fuel for diesel engines available in the market for the public in Nigeria.

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