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Reactor Design for Biodiesel Production from Palm Fatty Acid Distillate using the Esterification Method

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Abstract (English)
This research aims to design a biodiesel production reactor from Palm Fatty Acid Distillate (PFAD) using the esterification method. PFAD was chosen as an alternative raw material because the price is more economical. The biodiesel synthesis process involves a mixture of PFAD, methanol, and sulfuric acid catalyst (H2SO4) in a vertical cylindrical reactor. The calculation results show that the reactor with a total volume of 52.4527 ft^3, vessel dimension 40.7673 in, and cylinder thickness 0.0683 in meets the design specifications. The esterification process took place for 60 minutes at a temperature of 60°C and atmospheric pressure, resulting in a Free Fatty Acid (FFA) conversion of 98%. An axial turbine stirrer with a power of 1342 HP is used to ensure optimal reaction efficiency. The reactor and stirrer have been designed with adequate specifications, so that the design and performance analysis of the reactor can be applied in industrial scale biodiesel production.

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Biodiesel production, Palm Fatty Acid Distillate, Esterification, Reactor design.

Abstrak (Indonesia)
Penelitian ini bertujuan untuk mendesain reaktor produksi biodiesel dari *Palm Fatty Acid Distillate* (PFAD) menggunakan metode esterifikasi. PFAD dipilih sebagai bahan baku alternatif karena harganya yang lebih ekonomis. Proses sintesis biodiesel melibatkan campuran PFAD, metanol, dan katalis asam sulfat (H_2SO_4) dalam reaktor silinder tegak. Hasil perhitungan menunjukkan bahwa reaktor dengan total volume 52.4527 ft^3, vessel dimension 40.7673 in, dan cylinder thickness 0.0683 in untuk memenuhi spesifikasi desain. Proses esterifikasi berlangsung selama 60 menit pada suhu 60°C dan tekanan atmosfer, menghasilkan konversi *Free Fatty Acid* (FFA) sebesar 98%. Pengaduk axial turbine dengan daya 1342 HP digunakan untuk memastikan efisiensi reaksi yang optimal. Reaktor dan pengaduk telah didesain dengan spesifikasi yang memadai, sehingga desain dan analisis kinerja reaktor dapat diaplikasikan dalam produksi biodiesel skala industri.

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Kata Kunci
Produksi biodiesel, Palm Fatty Acid Distillate, Esterifikasi, Desain Reaktor.

Introduction

Biodiesel is an environmentally friendly alternative fuel and is produced from renewable natural resources. The commonly used biodiesel raw materials are vegetable oils and animal fats. However, the price of these raw materials is relatively high so it is necessary to look for cheaper alternative raw materials. Palm Fatty Acid Distillate (PFAD) is a by-product of palm oil processing which contains high levels of free fatty acids (FFA). PFAD has the potential to be used as a raw material for biodiesel because its price is relatively cheap (Arismunandar, 2001).

The biodiesel production process from PFAD consists of two stages, namely esterification and transesterification. In the esterification stage, the FFA in PFAD is converted into ester with the help of a catalyst. In the transesterification stage, the triglycerides in PFAD are converted into esters with the help of a catalyst and methanol. The esterification reactor is one of the most important operating units in the biodiesel production process from PFAD. Optimal esterification reactor design will produce high FFA conversion with high efficiency (Budiman, 2017).

The results of research that have been carried out reveal a number of factors that significantly influence the conversion of Free Fatty Acid (FFA) in esterification reactors. These key factors include the type of catalyst used, reaction temperature, reaction time, methanol to Palm Fatty Acid Distillate (PFAD) ratio, and stirring speed. The type of catalyst is a determining factor that influences the conversion efficiency of FFA, while the reaction temperature, reaction time, and methanol to PFAD ratio form important parameters that jointly contribute to the reaction outcome. Stirring speed has also been proven to play a role in optimizing the esterification process, indicating that each of these factors has a special role in influencing the performance of the esterification reactor (Setiawati, 2012).

Esterification reactors commonly used for biodiesel production from PFAD are batch reactors and stirred tank flow reactors. Batch reactors have the advantage of relatively low investment costs, but the resulting FFA conversion is also relatively low. Stirred tank flow reactors have the advantage of high FFA conversion, but the investment costs are relatively high (Budiman, 2017).

The aim of this research is to design a reactor for biodiesel production from PFAD using the esterification method. The proposed reactor design is expected to produce high FFA conversion with High energy efficiency too.

Research Methods

Biodiesel Synthesis

PFAD is mixed with methanol and sulfuric acid catalyst (H_2SO_4) in a reactor, then heated at a temperature of 60°C to 65°C for 2-3 hours. The transesterification reaction will take place, producing biodiesel and glycerol. Biodiesel is then separated from glycerol and residual methanol through an evaporation process.

The biodiesel production process using PFAD as raw material can produce biodiesel with a high yield, namely around 95%. This biodiesel can be used as a substitute for diesel fuel. The biodiesel production scheme is explained in detail in Figure 1 and Figure 2 will explain the reaction mechanism that occurs.

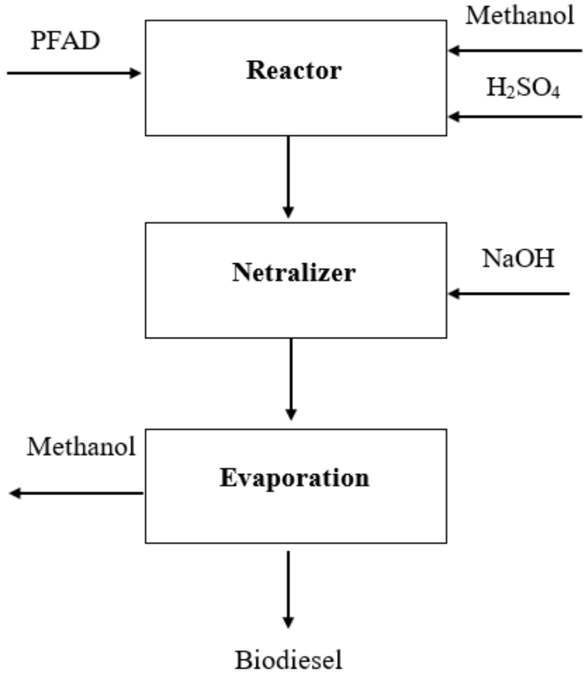

Figure 1 Biodiesel Production Scheme from PFAD

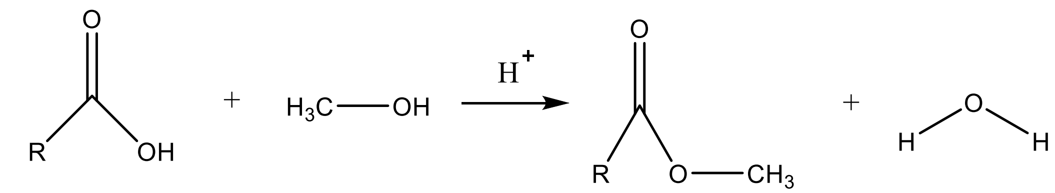

Figure 2 Esterification Reaction

Design Reactor

The reactor used is an upright cylindrical reactor with a standard lid and a conical base with a top angle of 120°. The reactor operating temperature is 60°C, operating pressure is 1 atm, and operating time is 1 hour. The reactor construction material is stainless steel SA 240 Grade M Type 316 with an allowable stress of 18750. The corrosion factor used is 0.0625. The stirrer used is an axial turbine stirrer with 4 blades at a 45° angle. The stirrer impeller material is high alloy steel SA 240 Grade M type 316, while the stirrer shaft material is hot roller steel SAE 1020. The reactor and stirrer design specifications need to be considered so that the biodiesel production process can run smoothly and produce good quality biodiesel. Details Specification assumptions can be found in table 1.

Table 1 Assumptions of specifications design of reactor and stirrer

Specifications	Reactor
Type	Upright cylinder with standard dished top and conical bottom with 120˚ apex angle
Temperature	60˚C
Pressure	1 atm
Operation time	1 hour
Construction time	Stainless steel SA 240 Grade M Type 316
Allowable Stress (*f*)	18750
Welding	Double welded butt joint
Corrosion Factor	0.0625
Amount of incoming substance	2125.47 lb/d
Volumetric rate	50.6519 ft^3/h
	Stirrer
Type	Axial Turbine with 4 Blades at an Angle of 45˚
Material impeller	High Alloy steel SA 240 Grade M type 316
Shaft materials	Hot Roller Steel SAE 1020

The reactor operated for 60 minutes at a temperature of 60°C and atmospheric pressure. The amount of substance that entered was 2125.47 lb/h. Mass balance analysis was carried out using the Microsoft Excel application. Equation 1-18 is used to collect and calculate data. Table 2 presents the calculated parameters for the reactor and stirrer (Anggraini, 2018).

Table 2 Calculation of reactor and stirrer parameters

Sections	Parameters	Equations	Eq
Dimensions of reactors	Total Volume of Reactor	$Total\ Vol.of\ reactor = precursor\ vol. + 20\% \times blank\ psace\ Vol.$ Where Total vol. of reactor (ft^3)	(1)
	Vessel dimensions (d_i)	$Total\ Vol. = V_{bottom\ lid} + V_{cylinder} + V_{top\ lid}$ $Total\ Vol. = \left(\frac{\pi d_i^3}{24\tan\left(\frac{1}{2}\alpha\right)}\right) + \left(\frac{\pi d_i^3}{4} \times Lc\right) + 0.0847 d_i^3$ Where α = 60˚ L_c = 1.5 *in* _ (in)	(2)
	Volume of liquid in the cylinder (V_{lc})	$V_{lc} = V_{liquid} - V_{bottom\ lid}$ Where V_{lc} (ft^3)	(3)
	Height of liquid in the cylinder (H_{lc})	$H_{lc} = \frac{V_{lc}}{\left(\frac{\pi}{4}\right) d_i^2}$ Where H_{lc} (in)	(4)

	Pressure of design (Pi)	$P_i = P_{atm} + P_{hydrostatic}$ $P_i = 14{,}7\ psia + \left(\frac{\rho(HL-1)}{144}\right) psia$ Where HL = 5.1463 P_i (psig)	(5)
	Cylinder thickness (tc) and d_o standardization	$t_c = \left(\frac{p_i \times d_i}{2(f \times E - 0.6P_i)}\right) + C$ Where f = 18750 E = 0.8 C = 1/16 $d_o = d_i + 2t_c$ Where d_o (ft)	(6)
	Height of cylinder (Lc)	$Total\ Vol. = V_{bottom\ lid} + V_{cylinder} + V_{top\ lid}$ $Total\ Vol. = \left(\frac{\pi d_i^3}{24 \tan\left(\frac{1}{2}\alpha\right)}\right) + \left(\frac{\pi d_i^3}{4} \times Lc\right) + 0.0847 d_i^3$ L_c (in)	(7)
	Dimensions of top lid	$th_t = \frac{0.885 \times P_i \times d_i}{2(f \times E - 0.1P_i)} + C$ Where th_t= top lid thickness (in) $h_t = 0.169 \times d_i$ Where h_t= height of top lid (in)	(8)
	Bottom lid dimensions	$th_b = \frac{P_i \times d_i}{2(f \times E - 0.16)\cos\left(\frac{1}{2}\alpha\right)} + C$ Where α= 120° th_b= bottom lid thickness (in) $h_b = \left(\frac{\frac{1}{2}h_t}{\tan\left(\frac{1}{2\alpha}\right)}\right)$ Where α= 120° h_b= height of bottom lid (in)	(9)
	Height of reactor	$Height\ of\ reactor = h_t + L_c + +h_b + s_f$ Where s_f= 2.5 Height of rector (ft)	(10)
Stirrer	Impeller diameter (D_a)	$\frac{D_a}{D_t} = 0.5$ Where D_t= 77.6250 Impeller diameter (ft)	(11)
	height from the bottom of the	$\frac{Z_i}{D_t} = \frac{1}{3}$	(12)

tank (*Zi*)	Where Impeller diameter from the bottom of the tank (ft)	
Impeller length (*l*)	$$\frac{l}{D_a} = \frac{1}{4}$$ Where Impeller length (ft)	(13)
Impeller width (*W*)	$$\frac{W}{D_a} = \frac{1}{5}$$ Where Impeller width (ft)	(14)
Number of stirrers (*n*)	$$n = \frac{H_{liquid}}{2 \times D_a^2}$$ Where H_{liquid}= 61.7559	(15)
The stirring power (*H*)	$$P = \frac{\varphi \times \rho \times n^3 \times D_i^5}{g_c}$$ Where φ= 0.9 g_c = 32.2 lb.ft/s ^{2} .lbf *P* (Phone) $$H = (0.1 + 0.15)P + P$$ Where 0.1 = estimation of the amount of power leakage in the process and bearing from the input power 0.15 = estimation of the amount of belt or gear leakage form input power *H* (Cellphone)	(16)
Shaft diameter of stirrer (*D*)	$$D^3 = \frac{16 \times T}{\pi \times S}$$ $$T = \frac{63025 \times H}{N}$$ $$S = 20\% \times 36000\ lb/in^2$$ Where *S*= maximum allowable design shearing stress (lb/in ^{2}) *N* = stirrer rotation = 100 rpm *T* = torque moment (lb.in) π= 3 *D* (in)	(17)
Shaft length of stirrer (*L*)	$$L = h + (l - Z_i)$$ Where $h = L_c + h_t$ *L* (ft)	(18)

Result and Discussion

Esterification and transesterification reactions for the production of palm fatty acid distillate (PFAD) biodiesel can be carried out using a stirred tank reactor. This reaction requires a certain temperature and pressure to take place optimally. Based on the calculation results using the equation in table 2, the reactor for biodiesel production from PFAD has a vessel dimension of

40.7673 in, height of reactor of 2.0568 ft, total volume of reactor of 52.4527 ft^3, height of cylinder of 4.5164, and other parameters are explained in the table 3.

Table 3 Reactor parameters designed based on calculations.

No	Parameters	Results
1	Total volume of reactors	52.4527 ft^3
2	Vessel dimensions (d_i)	40.7673 in
3	Volume of liquid in the cylinder (V_{lc})	38.9998 ft^3
4	Height of liquid in the cylinder (H_{lc})	51.6550 in
5	Pressure of design (*Pi*)	4.3040 psig
6	Cylinder thickness (*tc*)	0.0683 in
7	D_o standardization	40.9040 in
8	Height of cylinder (*Lc*)	4.5164 in
9	Top lid thickness (th_t)	0.0676 in
10	Height of top lid (h_t)	6.8896 in
11	Bottom lid thickness (th_b)	0.0742 in
12	Height of bottom lid (h_b)	11.7824 in
13	Height of reactor	2,0568 ft

This reactor is cylindrical in shape with walls made of Stainless steel SA 240 Grade M Type 316. The reactor walls have a cylinder thickness of 0.0683 inches to withstand operating pressure. The reaction takes place in the reactor cylinder, which is filled with a mixture of PFAD, methanol and catalyst. The mixture was heated to a temperature of 60°C using a heating device. After reaching the reaction temperature, the mixture is stirred at a certain speed to speed up the reaction. The reaction lasted for 60 minutes to achieve FFA conversion of 98%.

In this reactor, 1 stirrer is used, Axial Turbine type with 4 Blades at an Angle of 45˚. After carrying out calculations, the parameters for the stirrer were obtained, such as impeller diameter of 38.8125 ft, impeller length of 9.7031 ft, stirring power of 1342 HP, shaft length of stirrer of 2.5689 ft, and the parameters are explained in more detail in table 4.

Table 4 Stirrer parameters designed based on calculations.

No	Parameters	Results
1	Impeller diameter (D_a)	38.8125 ft
2	height from the bottom of the tank (*Zi)*	25,875 ft
3	Impeller length (*l*)	9,7031 ft
4	Impeller width (*W*)	7.7625 ft
5	Number of stirrers (*n*)	1 piece
6	The stirring power (*H*)	1342 HP
7	Shaft diameter of stirrer (*D*)	8.5575 in
8	Shaft length of stirrer (*L*)	2,5689 ft

Conclusion

The reactor and stirrer design has the necessary specifications to ensure a smooth biodiesel production process. The reactor is cylindrical with stainless steel walls, with specifications for a total volume of reactor of 52.4527 ft^3 with a height of reactor of 2.0568 ft and a cylinder thickness of 0.0683 in. The stirrer uses a single stirrer axial turbine impeller with a power of 1342 HP.

Calculations were carried out using Microsoft Excel without considering effectiveness factors. Based on the calculation results, it can be concluded that the design and performance analysis of the reactor can be applied.

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