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Thermodynamic Analysis of Biodiesel Production with Catalyst and Non-Catalyst Process: Incase Energy Analysis

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ABSTRACT

Biodiesel production from renewable resources needs a certain amount of energy Input. The effectiveness of biodiesel production depends on the energy ratio, i.e. the ratio of energy contained in the biodiesel to the energy input during production, including energy content in the feedstock. The objective of the study is aimed to evaluate the energy ratio in biodiesel production. The input and output energy were analyzed for each process (catalyst and analysist). Materials required in biodiesel production was evaluated in term of their energy content. The equipment used to obtain data on the non-catalytic biodiesel production process was a prototype bubble column reactor designed by the Department of Global Agricultural Sciences at The University of Tokyo, Japan and data on the catalytic biodiesel production process was obtained from the Center for Design and Technology System Engineering, BPPT Serpong,by the design of the equipment owned by the institution. The results showed that the energy ratio and the energy needed to produce per kilogram of biodiesel using the non-catalytic production method with a modified process were 1.00 and 39.63 MJ/kg while using the catalytic method were 0.98 and 41.05 MJ/kg, respectively. The non-catalytic production method with a modified process is better than the catalytic method in energy ratio. The energy needed to produce per kilogram of biodiesel due to the heat exchanger is critical for the performance improvement of the modified non-catalytic process.

Keywords: biodiesel, energy, energy ratio, CPO, thermodynamic

1. Introduction

Energy efficiency is essential when selecting biodiesel production equipment and application processes. It is essential to determine the energy ratio of each industrial step to build a more energy-efficient biodiesel production method. This ratio compares biodiesel's calorific value with the feedstock's energy content and the energy required during the production process, such as thermal and electrical energy. When the energy given to produce per kilogram of biodiesel is utilized in such a way, the energy lost can be minimized. The energy formed from the chemical reaction process when mixing triglycerides (TG) with methanol (MeOH) must be considered input energy. The amount of energy required will affect biodiesel production's energy ratio and efficiency. In each production process, biodiesel's energy is expected to be greater than the energy required.

Trans esterifying triglycerides obtain biodiesel with alcohols in the presence of catalysts, biocatalysts, or without catalysts [1]. Traditional biodiesel production processes are named after the types of catalysts used, including acidic, alkaline, and enzymatic, all in a uniform form. The use of catalysts aims to shorten the reaction time and achieve the desired reaction conditions [2]. A *widespread variant* is an alkaline reactor, which uses a batch reactor with a reaction time of 1 h, 1 atm, 65 °C, and typical alcohol to triglyceride molar ratio of 6:1 [3]. These conditions are achieved by adding KOH, NaOH, or CH_3ONa [4]. However, this type of catalyst interferes with the separation process. If no attention is paid to the free fatty acid (FFA) content, the resulting reaction will produce soap instead of biodiesel [4]. Heterogeneous catalysts for biodiesel production, consisting mainly of oxides, metals, zeolites, or animal wastes with high calcium content, are currently being investigated [5-6]. Once biodiesel is available, these catalysts simplify the separation process at a lower cost than traditional chemicals. One of the main drawbacks is the long reaction time compared to homogeneous catalysts [7].

Supercritical processes allow the use of lower-quality raw materials for biodiesel production, for instance, oils with high levels of FFA or moisture. This process converts triglycerides directly into biodiesel. Neither FFA nor water will harm the process. Several studies on non-catalytic transesterification processes using methanol and ethanol have been performed at temperatures ranging from 280 to 425 °C, pressures ranging from 8 to 43 MPa, and ratios of alcohol to oil ranging from 6:1 to 50:1. A molar ratio was carried out. Reaction times range from 4 to 90 minutes, depending on the type of oil and the equipment used. These variables influence process effectiveness and biodiesel yield [8]. [9-10] have reported the economic analysis of the biodiesel synthesis procedures utilizing homogeneous alkaline catalysis and supercritical technique. It was discovered that energy usage is comparable in both instances, but expenses are offset by the less expensive purifying method. [11] discovered that, from a technological standpoint, a supercritical approach is an attractive option since it produces less wastewater and generates high-quality glycerin as a by-product. Nevertheless, the reaction step requires more energy. In this study, energy analysis was carried out at each station in the catalytic and non-catalytic biodiesel production process to develop a more energy-efficient production process.

2. Materials and Methods

2.1Materials

Refined palm oil with the following characteristics: iodine value 50-55, free fatty acid (as oleic acid) 0.1% w/w, myristic acid 0.5-5.9% w/w. /w. palmitic acid. Stearic Acid, 2-8% w/w; Oleic Acid, 34-44% w/w; Linoleic Acid, 7-12% w/w and Methanol p.a. (Pro analysis) of minimum 99.8% purity [12] were used as materials.

The equipment used to obtain data on the non-catalytic biodiesel production process was a prototype bubble column reactor designed by the Department of Global Agricultural Sciences at The University of Tokyo, Japan (Figure 1). The prototype data has been equipped with the necessary measuring and control equipment. Data on the catalytic biodiesel production process was obtained from the Center for Design and Technology System Engineering, BPPT Serpong,by the design of the equipment owned by the institution with 1 ton per batch (Figure 2).

The biodiesel production process without a catalyst using a reactor capacity of 200 mL is shown in Figure 1. In the first step, filled reactor with oil to 200 mL through B1, nitrogen gas (N2) with a pressure of 0.3 - 0.5 MPa flowed until the oil flow pipe was filled with N2 so that the oil did not flow into the methanol flow pipe in the hope that the oil and methanol will react only in the reactor. Nitrogen gas was expelled through O1. Furthermore, the oil in the reactor is heated until it reaches a temperature of 290 ^{o}C. The second step flowed methanol from the methanol tank at a rate of 3.0 mL/min of methanol to be fed before the N2 flow was stopped. The methanol evaporates through two heat exchangers (HE), which have temperatures of 150 ^{o}C and 200 ^{o}C located at the evaporator station. Furthermore, the methanol flows through the superheater station, which also has two HE with temperatures of 250 ^{o}C and 290 ^{o}C, and then the methanol vapour that passes through the superheater flows into the reactor through bubbles; this flow occurs continuously.

In the third step, pump oil continuously from the oil tank through valve V3 and maintain the reactor at 200 mL. If the reactor has reached the level, the excess oil will be accommodated through O2. The product of the reaction is in the form of a vapour phase and then condensed and accommodated through F1.

On the other hand, in biodiesel production with a catalyst process, several steps are involved. The first step is NaOH catalyst and methanol, which has a temperature of 27 ^{o}C mixed into a Mixed Methanol Tank (MMT); then, a mixture of catalyst and methanol was pumped into the reactor. Refined oil is also pumped into the reactor and stirred using an electromotor. The product mixture was pumped to the Washed Tank (WT) for washing in the next step by adding hot water at 80 ^{o}C.

Finally, the product was analysed to determine the content of biodiesel and glycerol (GL) as by-products. From these data, a mass balance determines the energy and exergy balance so that the energy ratio and exergy efficiency can be calculated.

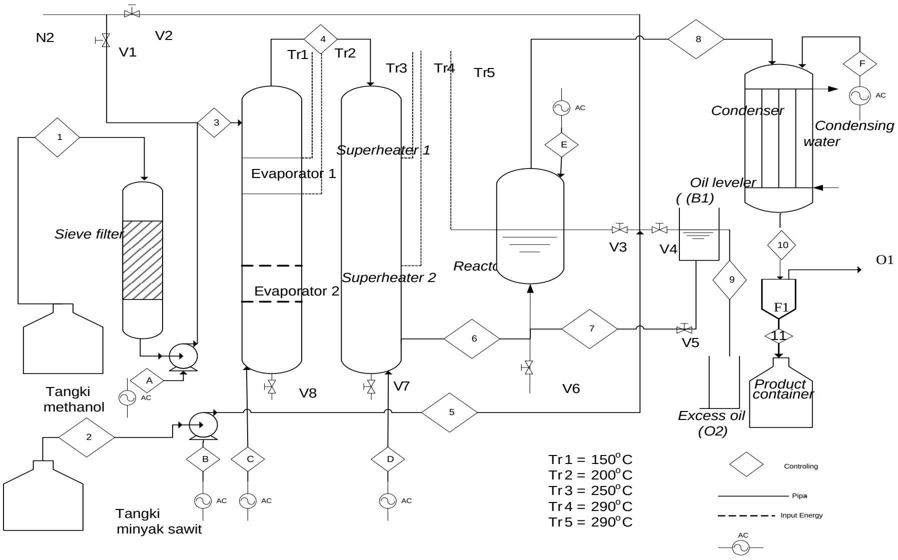

Figure 1. Scheme of biodiesel production process without catalyst (non-catalyst)

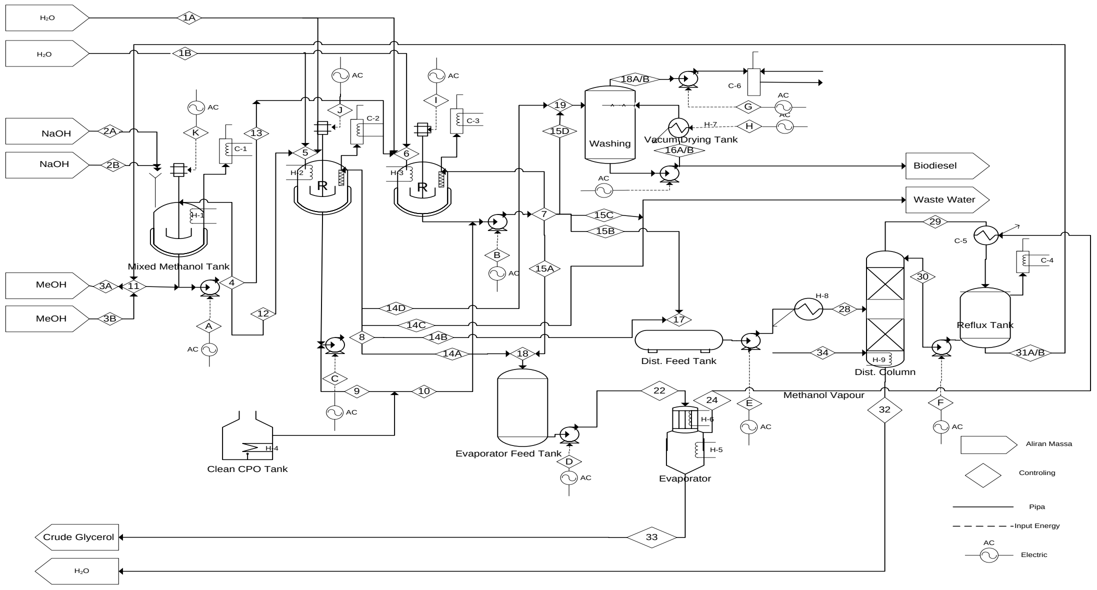

Figure 2. Scheme of biodiesel production process with catalyst

Table 1. The molecular weight of fatty acids in triglycerides (TG)

Fatty acid	Molecular weight (gr/gmol)	Percentage (%)	Molecular weight in TG* (gr/gmol)
Palmitic acid (**$C_{16}H_{32}O_2$**)	256	34.98	268.65
Stearic acid (**$C_{18}H_{36}O_2$**)	284	13.78	117.42
Oleic acid (**$C_{18}H_{34}O_2$**)	282	41.23	349.11
Linoleic acid (**$C_{18}H_{30}O_2$**)	272	10.01	81.68
Total		100	816.87

**TG= triglycerides*

The scale enlargement and modification of the non-catalytic biodiesel production process were carried out from a laboratory scale to a scale of 1 ton/hour for biodiesel production using the stoichiometric concept. The molecular weight of TG is first calculated based on the acid composition contained in the oil can be seen in Table 1. While the molecular weight of Methyl Ester/ME (biodiesel) is calculated from the percentage of fatty acid molecular weight, the same as in TG, the structure of ME only consists of one alkyl, as shown in Figure 3.

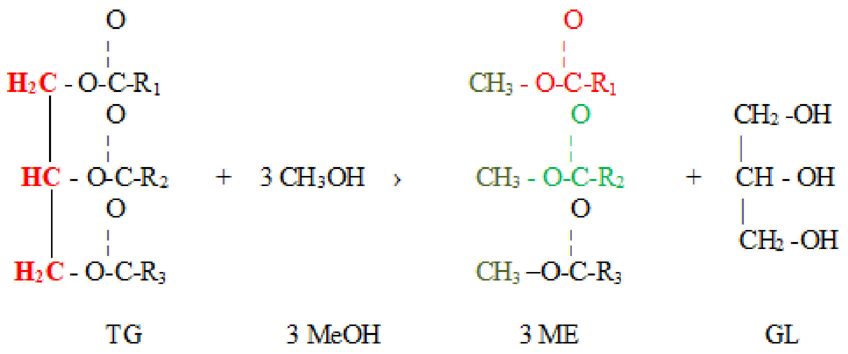

Figure 3. The molecular structure of triglycerides, methanol, methyl esters and glycerol

The molecular weight of methanol is calculated based on the C and H atoms in the methanol structure. The glycerol molecular weight (GL) is calculated based on the molecular structure's C, O and H atoms, as displayed in Table 2.

Table 2. The molecular weight of each chemical element

	Molecular weight (gr/gmol)
Triglycerides (TG)	858
Methyl ester (ME)	287
Methanol	32
Glycerol	92
NaOH	40

2.2 Data Analysis

2.2.1 Energy Analysis

The energy analyzed in the catalytic and non-catalytic biodiesel production process consists of heat and electrical energy. Thermal energy was used to heat the feed material and the resulting product. The energy formed in the exothermic reaction process in the reactor was calculated as input energy. Pumps and other electromotors used electrical energy. In a non-catalytic laboratory-scale production process, the required heating energy used electrical energy. The energy required for feed and product heating is calculated based on theory, not a direct measurement for the 1-ton scale. The energy content of NaOH (catalyst) was not determined with the assumption that it could be recycled.

The equations used to determine the heating energy of methanol, TG, ME, and GL as well as the catalyst are as Eq. (1), where is the mass flow rate (kg/s), c_p is the specific heat of the material (kJ/kg ^oC) and dT is the change in temperature (^oC).

$$Q = \int_{T_1}^{T_2} \dot{m} c_p \, dT \tag{1}$$

As long as methanol changes phase from liquid to gas, the amount of energy was determined based on Eq. (2), where h_{fg} is the heat of vaporization (kJ/kg), dw is the mass of the material changing phase (kg), while dt is the change in time during the production process (s).

$$Q = \int_{t_1}^{t_2} h_{fg} \frac{dw}{dt} \tag{2}$$

The phase change of methanol from liquid to gas when the temperature in the system is above 65 ^oC. The phase changes of methanol, ME and GL was determined the latent heat value of methanol. The total energy required can be calculated by Eq. (3).

$$Q = \int_{T_1}^{T_2} \dot{m} c_p \, dT + \int_{t_1}^{t_2} h_{fg} \frac{dw}{dt} + \int_{T_{g1}}^{T_{g2}} \dot{m} c_p \, dT \tag{3}$$

The amount of oil reacted with methanol produced glycerol (GL), and biodiesel was calculated stoichiometrically based on Eq. (4).

$$\text{TG} \quad + \quad 3\,CH_3OH \quad \rightarrow \quad 3\,\text{ME} \quad + \quad \text{GL} \tag{4}$$

The electrical energy consumed during biodiesel processing can be expressed by Eq. (5), where P is the electric power used by both pumps and electromotors during the biodiesel production process.

$$Q = \int_{t_1}^{t_2} P \, dt \tag{5}$$

The energy ratio (RE) was calculated by Eq. (6), where RE is the energy ratio, E_{out} is the energy output (kJ), and E_c is the energy content of the raw materials used (MeOH and oil) in kJ/kg. At the same time, $E_{process}$ is the heat energy used to raise process temperature (kJ).

$$R_E = \frac{E_{out}}{E_c + E_{proses}} \tag{6}$$

$$E_{in} = E_c + E_{proses} \tag{7}$$

$$E_c = E_{MeOH} + E_{oil} \tag{8}$$

$$E_{proses} = E_{listrik} + E_{panas} \tag{9}$$

$$E_{out} = E_{FAME} \tag{10}$$

Energy output (E_{out}) is biodiesel's energy content without considering the energy of glycerol and soap as by-products.

3. Results and Discussion

3.1 Energy Analysis of Biodiesel Production Process

3.1.1 Non-catalyst Process

Energy analysis in non-catalytic biodiesel production was carried out in three stages: laboratory scale, scale-up of the biodiesel production process to 1 ton per hour and modifying the biodiesel production process on a scale of 1 ton per hour.

Energy analysis in the non-catalytic biodiesel production process was carried out on a laboratory scale with a reactor volume of 200 mL. This process takes place continuously. Methanol is flowed using a pump with a power of 30 watts to the evaporator and super heater before entering the reactor at a rate of 3 ml/min (Figure 1). The temperature of the evaporator and super heater corresponds to the reaction temperature in the reactor. The oil that has been filled into the reactor is also heated according to the reaction temperature (290 ^{o}C).

Table 3. Laboratory-scale non-catalytic biodiesel production mass balance

	Input mass rate (g/hour)	**Output mass rate (g/hour)**	
Oil (TG)	25.64		
MeOH	142.2	139.49	
Biodiesel Products:		25.59	
Pure ME			24.34
uME			1.25
Glycerol Products:		2.736	
Pure GL			2.607
uME			0.129
Unreacted Oil (TG)		0.03	
Total	167.84	167.84	

The measurement results in the study showed that biodiesel production was 25.59 g/hour with an oil feed rate (assuming 100% TG) of 25.69 g/hour or equivalent to 0.03 gmol/hour. The purity of the ME produced is 95.1 % w/w, equivalent to 24.34 g/hour means a part of the oil has not reacted but is included in the product at 1.25 g/hour. The portion of the product that did not undergo methanolysis reaction was expressed as un-methyl-esterified (uME). The amount of methanol required is 142.2 g/hour, equivalent to 4.44 gmol/hour, and the reacted methanol is only 2.72 g/hour. This result shows that there is unreacted methanol of 139.48 g/hour. Thus, the mole ratio of methanol to oil is 148 (mol/mol). The ratio of methanol to oil required in non-catalytic processes is much greater than in catalytic processes.

The glycerol (GL) produced in this study was 2.736 g/hour, while the GL formed based on the stoichiometric equation (Eq. 4) was 2.607 g/hour. This means that a GL is contained in the unreacted oil (uME) of 0.129 g/hour. Based on the mass balance (Table 3), there is 0.03 g of oil remaining in the reactor, and it does not react with methanol.

The heat energy required to vaporize methanol in the evaporator and super heater and to heat the oil to a temperature of 290 °C (Table 4) was calculated by Eqs. (1), (2), and (3) with assumed that the heating efficiency was 70%.

Table 4. Thermal energy required in laboratory-scale non-catalytic production processes

	Heat energy		**Specific energy**	
	(kJ)	**(MJ)**	**(kJ/kg ME)**	**(MJ/kg ME)**
Evaporator -1	140.48	0.14	5489.64	5.49
Evaporator -2	17.47	0.02	682.69	0.68
Superheater -1	19.70	0.02	760.84	0.76
Superheater -2	15.76	0.02	615.86	0.62
Reactor	6.75	0.01	263.78	0.26
Total	200.17	0.20	7,822.20	7.82

The mass balance for a production scale of 1 ton/hour was obtained through a laboratory scale-up with a 200 mL reactor volume described above. Scale enlargement was made theoretically based on the concept of stoichiometry with the assumption of 100% process and tool efficiency. The results obtained are shown in Table 5.

Table 5. Mass balance in the non-catalytic process of biodiesel production on a 1 ton scale

	Input mass rate (kg/hour)	**Output mass rate (kg/hour)**	
Oil (TG)	1,001.71		
MeOH	5,550.73	5,444.69	
Biodiesel Products:		1000	
Pure ME			951
uME			49
Glycerol Products:		106.64	
Pure GL			101.62
uME			5.02
Unreacted Oil (TG)		1.1	
Total	6,552.43	6,552.43	

Suppose the production process of 1 ton of biodiesel per hour is based on laboratory-scale productivity. In that case, the volume of oil in the reactor is 7.8 m^3 (rounded to 8 m^3), the flow rate of methanol is 5550.73 kg/hour (density of methanol 790 kg/m^3), and the volume of methanol is 7.03 m^3.

Based on the mass balance in Table 6, it is obtained the amount of heat energy to evaporate methanol in the evaporator and super heater as well as to heat oil in the production of biodiesel on an hourly production scale. The most significant heat energy requirement is to evaporate MeOH in evaporator-1 due to the significant difference in methanol temperature, assuming that the heating efficiency is 70%. While the electrical energy required to flow oil and methanol by the pump based on the liquid flow rate was obtained from [13], as shown in Table 7.

Table 6. Thermal energy required in the non-catalytic biodiesel production process at a scale of 1 ton/hour

	Heat energy		Specific energy	
	(kJ)	**(MJ)**	**(kJ/kg ME)**	**(MJ/kg ME)**
Evaporator -1	5,483,442.8	5,483.4	5,483.44	5.48
Evaporator -2	681,946.3	681.9	681.95	0.68
Superheater -1	769,172.0	769.2	769.17	0.77
Superheater -2	615,337.6	615.3	615.34	0.62
Reactor	1,476,835.5	1,476.8	1,476.84	1.50
Total	9,164,576.9	9,164.6	9,164.58	9.16

Table 7. Electrical energy required by the pump to flow oil and methanol

	Power	time	Energy	
	(kW)	**(hour)**	**(kJ)**	**(MJ)**
Methanol pump	4.50	1.00	16,200.00	16.20
Oil pump	0.72	1.00	2,592.00	2.59
Total	5.22		18,792.00	18.79

The non-catalytic biodiesel production process can be modified so that the heat from the reactor is recycled and reused to heat and evaporate methanol so energy efficiency can be increased. The recycling requires four heat exchangers (HE), as shown in Figure 4, assuming the effectiveness of HE is 0.7 (Table 8).

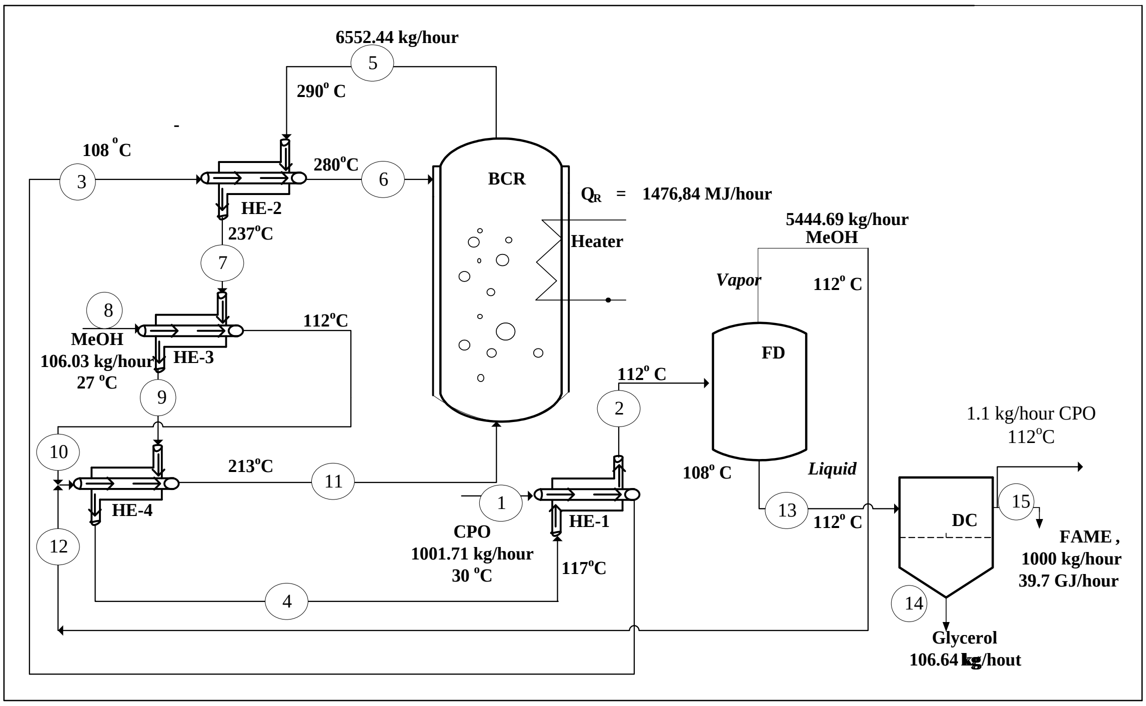

Figure 4. Flowchart of the non-catalytically modified biodiesel production process

The oil (temperature 30 °C) is flowed through HE-1 by utilizing the heat of the product coming out of HE-4 (temperature 117 °C) so that the oil temperature increases to 108 °C. Furthermore, the oil flows through HE-2 to exchange heat with the product stream at 290 °C coming out of the reactor, so the oil increases in temperature from 108 °C to 280 °C.

Table 8. Effectiveness of HE on a scale-up-scale biodiesel production process

		Heat		**effectiveness**			
		(kJ)	**(MJ)**	**HE-2**	**HE-3**	**HE-4**	**HE-1**
Q_R (5-7)	Hot	742958.83	742.96	0.70			
Q_1 (3-6)	cold	518604.85	518.60				
Q_2 (7-9)	Hot	179483.63	179.48		0.71		
Q_3 (8-10)	cold	127520.78	127.52				
Q_4 (9-4)	Hot	1358947.48	1358.95			0.70	
Q_5 (10,12-11)	cold	953059.57	953.06				
Q_6 (4-2)	Hot	336973.74	336.97				0.70
Q_7 (1-3)	cold	235181.27	235.18				

Methanol at 27 °C is preheated by utilizing heat from the product that passes through HE-3 and HE-4. Methanol passing through HE-3 will experience an increase in temperature from 27 °C and change phase to vapour until it reaches a temperature of 112 °C. Furthermore, the methanol vapour is flowed into HE-4 by utilizing the heat of the product, which still has a temperature of 223 °C, so that the methanol temperature increases again to 213 °C and then flows into the reactor, which has a temperature of 290 °C.

Table 9. Total heat energy required in the biodiesel production process, both on a laboratory scale, scale-up and modified systems

	Evaporator-1	***Evaporator-2***	***Superheater-1***	***Superheater-2***	**Reactor**	**Total**	**Specific energy**
	(MJ)	**(MJ)**	**(MJ)**	**(MJ)**	**(MJ)**	**(MJ)**	**(MJ/kg ME)**
Laboratory	0.14	0.02	0.02	0.02	0.01	0.20	7.82
Scale-up 1 ton biodiesel	5,483.44	681.95	769.17	615.34	1,476.84	9,026.74	9.03
Modification process	0.00	0.00	0.00	0.00	1,476.84	1,476.84	1.5

Thus, the thermal energy required to increase the temperature of the feed oil entering the reactor at 290 °C can be minimized. Thus, the heat energy required to produce non-catalytically modified biodiesel is only to maintain the reactor temperature.

A comparison of the thermal energy required between laboratory scale, scale-up, and modified processes is shown in Table 9. As expected, the specific energy for heating in the modified process is the smallest (1.5 MJ/kg ME).

3.1.2 Catalyst Process

The mass balance in the catalytic biodiesel production process with a capacity of 1 ton of biodiesel per batch is shown in Table 10, and the flow chart is shown in Figure 5. This mass balance was obtained from secondary data from the catalytic process at the Center for Engineering Design and Technology Systems, Serpong (Figure 2).

Table 10. Mass balance in the catalytic biodiesel production process

	Input (kg/batch)		**Output (kg/batch)**	
Oil	1,045.66			
TG		1,039.2	11.8	
in biodiesel				7.16
in *crude glycerol*				1.56
in *waste water*				3.08
FA		5.42	5.42	
in biodiesel				3.78
in *crude glycerol*				0.02
in *waste water*				1.62
MeOH	523.96		412.504	
in biodiesel				0.12
in *waste water*				11.04
in *crude glycerol*				0.72
in *drying tank*				1.10
in *distilation column*				0.84
in *refluk tank*				397.601
losses in *refluk tank*				1.083
NaOH	11.04		1.64	
in *crude glycerol*				1.64
H_2O	1,770.9		1,770.9	
in *waste water*				1,045.60
in *crude glycerol*				3.46
in *distilation column*				706.9
in *methanol vapour*				14.86
in *vacuum dryer*				0.08
Biodiesel products:			1,007.3	
Pure ME				999.72
in *crude glycerol*				2.56
in *waste water*				5.02
Glycerol Products:			110.49	
Pure GL				19.35
in biodiesel				0.82
in *waste water*				4.98
in *drying tank*				0.82
in *distilation column*				15.72
in *refluk tank*				0.043
losses in pure GL				68.757
Soap			31.146	
in biodiesel				0.64
in *waste water*				3.00
in *crude glycerol*				8.32
in *vacuum dryer*				0.64
losses in *evaporator*				18.546
Impurities			0.2	
in biodiesel				0.02
in *waste water*				0.08
in *crude glycerol*				0.10
Total	3,351.56		3,351.56	

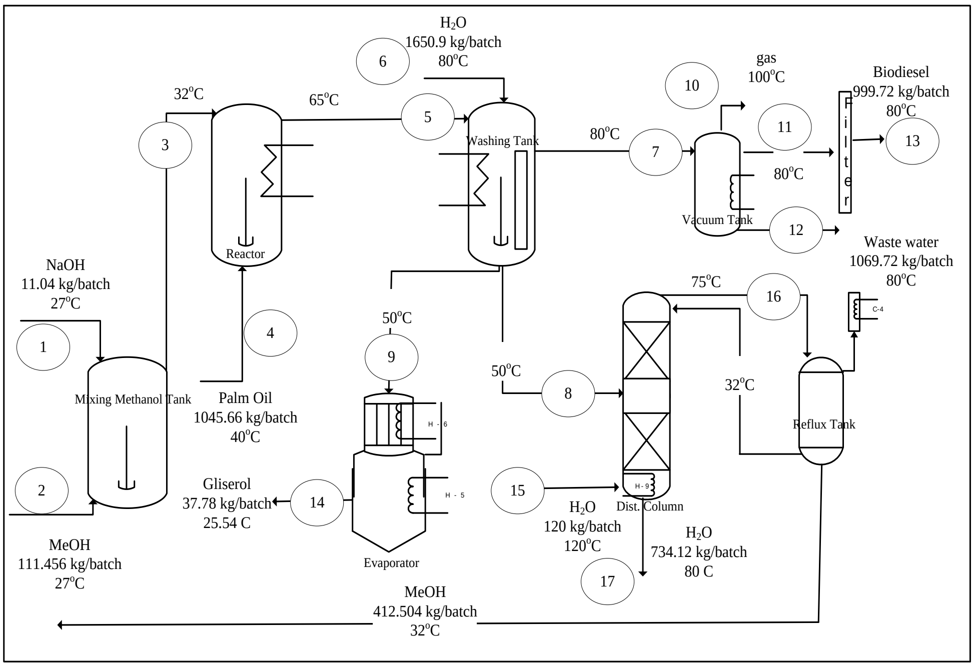

Figure 5. Mass balance flow in the catalytic production process

Table 11. Thermal energy required in the catalytic biodiesel production process

	Heat energy		**Specific energy**
	(kJ)	**(MJ)**	**(MJ/kg ME)**
Mixing Methanol Tank	10,217.80	10.22	0.0102
Reactor	-25,407.41	-25.41	-0.0254
Washing Tank	93,054.63	93.05	0.0935
Vacuum Dryer	220,037.16	220.04	0.2200
Evaporator Tank	29,287.80	29.29	0.0293
Distilation Tank	802,583.69	802.58	0.8026
Total	1,129,773.67	1,129.77	1.13

Table 12. Electrical energy required by pumps and electromotors for catalytic biodiesel production

	Power	**Time**	**Energy**	
	(kW)	**(hour)**	**(kJ)**	**(MJ)**
Mixed Methanol Pump	0.37	0.50	666.0	0,67
Reactor 1 Circulation Pump	1.10	1.00	3,960.0	3,96
Reactor 2 Circulation Pump	1.10	1.00	3,960.0	3,96
Drying Circulation Pump	1.10	2.00	7,920.0	7,92
Vacuum Pump	2.20	1.00	7,920.0	7,92
Evaporator Pump	0.20	3.33	2,397.6	2,40
Distillation Feed Pump	0.20	3.33	2,397.6	2,40
Reflux Pump	0.37	3.33	4,435.6	4,44
Cooling Tower Pump	0.75	3.33	8,991.0	8,99
Hot Water Pump	0.75	0.33	891.0	0,89
Mixer 2 Mixing Catalyst	1.10	0.50	1,980.0	1,98
Mixer 3 Reactor 1	1.50	1.00	5,400.0	5,40
Mixer 4Reactor 2	1.50	1.00	5,400.0	5,40
Total			56,318.8	5632

The heat energy required in the catalytic biodiesel production process is shown in Table 11. The thermal energy in the reactor is negative, indicating that the energy produced in the reaction process as a result of the exothermic reaction, based on the energy balance, is more significant than for product heating. The electrical energy required by pumps and electromotors to flow materials and products and to stir the mixture is shown in Table 12.

The energy content in the non-catalytic biodiesel production process at the laboratory scale and at a scale-up of 1 ton/hour, as well as in the catalytic biodiesel production, can be shown in Table 13.

Table 13. Energy content of feed materials and products in non-catalytic and catalytic biodiesel production processes

	mass (kg)			**Energy specific**	**Energy (MJ)**		
	Non-catalyst		**catalyst**	**(MJ/kg)**	**Non-catalyst**		**catalyst**
	laboratory scale	**Scale up 1 ton/hour**			**laboratory scale**	**Scale up 1 ton/hour**	
CPO	0.02564	1,001.71	1045.66	36.00	0.923	36,061.53	37,643.76
Methanol	0.00271	106.03	111.46	19.90	0.054	2,110.09	2217.97
Biodiesel	0.02559	1,000.00	999.72	39.70	1.016	39,700.00	39,688.88
residual CPO	0.00003	1.10	11.80	36.00	0.001	39.60	424.80

The total energy required to produce each kilogram of biodiesel can be shown in Table 14. The minor input energy per kg of biodiesel and the most considerable output energy is in the modified non-catalytic production process, namely 39.63 MJ/kg and 39.74 MJ/ kg.

Table 14. Energy input and output per kilogram of biodiesel production

Production process	**energy (MJ/ton biodiesel)**		**energy (MJ/kg biodiesel)**	
	Input	***Output***	***Input***	***Output***
catalytic	41,047.83	40,113.68	41.05	40.12
scale-up 1 ton non-catalytic process	47,315.41	39,739.60	47.32	39.74
Non-catalytic process scale-up modification	39,627.65	39,739.60	39.63	39.74

Table 15. Energy ratio of the non-catalytic and catalytic biodiesel production process

Production process	**heat energy (MJ)**		**electrical energy (MJ)**		**Energy content (MJ)**		**Energy ratio**
	Input	***Output***	***Input***	***Output***	***Input***	***Output***	
catalytic	1,129.77		56.32		39,861.73	40,113.68	0.98
scale-up 1 ton non-catalytic process	9,164.57		18.79		38,171.62	39,739.60	0.84
Non-catalytic process scale-up modification	1,476.84		18.79		38,171.62	39,739.60	1.003

Based on the heat and electrical energy required in the two processes and the feed material and product energy content, the ratio and energy efficiency are obtained, as shown in Table 15. According to Table 15, the most significant ratio is in the modified non-catalytic process. This result shows that using a Heat Exchanger (HE), which has an effectiveness of 0.7 on a modified non-catalytic process, can increase the energy ratio.

The energy content of CPO is 36.00 MJ/kg while the energy content of biodiesel is 39.70 MJ/kg (Table 14), so naturally, the ratio of the energy content of biodiesel to CPO is 1.10. The process of converting CPO into biodiesel always requires energy in the form of heat energy and electrical energy, so if the energy of the process is taken into account, the energy ratio must be less than 1.10. This result shows that achieving the energy ratio of 1.00 in the modified non-catalytic production process is the best. Table 15 shows that the specific energy required to produce per kilogram of biodiesel in the non-catalytic biodiesel production process for laboratory scale and 1 tonne of biodiesel production is more significant than in the catalytic production process. However, if the regulatory system is used, the non-catalytic production process is better than the catalytic one. It can also be seen from the energy ratio that after modification, the non-catalytic production process is better than the catalytic production process.

4. Conclusion

The analysis showed that the energy ratio and the energy needed to produce per kilogram biodiesel using the non-catalytic production method with a modified process were 1.00 and 39.63 MJ/kg, while using the catalytic method were 0.98 and 41.05 MJ/kg, respectively. The non-catalytic production method with a modified process is better than the catalytic method in energy ratio. The energy needed to produce per kilogram of biodiesel due to the heat exchanger is critical for the performance improvement of the modified non-catalytic process.

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