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A Comparative Study of the Impact of the Stirrer Design for Biodiesel Production

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Abstract— *Biofuels are becoming more widely recognized as a solution to the energy crisis and reducing dependency on fossil fuels. The cost of raw materials for biodiesel manufacturing is a significant challenge. To improve yield while lowering costs, the process must be optimized. As a result, mixing properties such as stirrer design, blade diameter, and stirrer location were optimized. This study used five blades to evaluate the Stirrer design on biodiesel production: cross stirrer, straight stirrer, blade stirrer, centrifugal stirrer, and pitched blade stirrer. The fluid mixing flow pattern was also examined and analysed. A pitched blade produced the best results, with the biodiesel meeting ASTM requirements. In contrast to the pitched stirrer, the Cross, Blade, and Straight stirrers have radial flow patterns. The centrifugal stirrer's radial and axial flow patterns were difficult to distinguish. Axial flow is essential for transesterification to avoid catalyst deposition at the reactor's bottom. The chosen blade's h/H (blade location from reactor bottom to fluid height) and d/D (blade diameter to reactor diameter) ratios were fine-tuned. The maximum yield was achieved with a h/H of 0.4 and a d/D of 0.3. Using a Pitched blade stirrer with 0.3 d/D and 0.4 h/H, the transesterification reaction yields 98%.*

Keywords— *Biodiesel, Mixing, Stirrer design, Transesterification, Yield.*

I. INTRODUCTION

The energy crisis still plays a significant threat to the economic recovery worldwide. The skyrocketing energy prices are paralyzing most of the nations. The majority of the air pollution is caused by fossil fuel combustion, especially coal and diesel, for electricity generation, transportation, and power generation in the industrial sector [1]. Energy-related fossil fuel combustion and biomass combustion account for more than 85% of the air pollution worldwide [2]. Fossil fuel combustion is considered the main contributor to greenhouse gas emissions and global warming [3]. It should mention that the prudent response to climate change is to adopt a vital action aimed at mitigation, adaptation, and research. Therefore, technological measures have to be immediately implemented to reduce emissions from power generation. Fossil fuel sources are the primary sources of air pollution by emitting Nitrogen oxides, Sulphur oxides, and carbon oxides [4]. Therefore, immediate implementation of biofuel is vital to replace fossil fuel consumption worldwide. Biodiesel production is the potential option to reduce the fossil fuel requirement for combustion applications in industries, transportation, and power generation. However, biodiesel yield is crucial in implementing the process with different oil sources. Yield can be calculated as the ratio between biodiesel productions per amount of oil consumed to produce that biodiesel. Conventional biodiesel processes given methyl ester, simply known as biodiesel and glycerine, which is the by-product of the process. Several pieces of research have been carried out to evaluate the impact of the reactor design on biodiesel production [5]. However, the biodiesel yield even depends on the mixing speed of the raw materials [6].

The mixing impact on biodiesel production has been considered in the present study. Therefore, five different stirs are used for the biodiesel production process separately and checked the reaction time, settling time, and biodiesel yield. The properties of the biodiesel are compared with the stirring effect to optimize the process.

1.1 Factors Effect on Mixing and the selection of the stirrer

There are multiple factors to be considered for the proper mixing and the selection of the stirrer design for the operation. Those can be categorized as;

1.1.1 Application of the process

During the process, what we should achieve or what to avoid. If it is important to avoid settling the solid at the bottom, then proper up and down mixing should perform. If it is essential to have a vortex, select the suitable blades for creating a vortex [7, 8, 9, 10].

1.1.2 Vessel Diameter

The size of the vessel used for mixing will determine the diameter of the impeller as it is a rule of thumb that for axial or radial flow patterns are, the diameter of the impeller should be 1/3 of the vessel's diameter.

1.1.3 Viscosity of the fluid

If it is a highly viscous fluid, proper material should be selected for the impeller and blade design. Otherwise, it will stick by the high viscous fluid shear. Moreover, blade angles and size should be appropriately designed according to the fluid viscosity [7, 8, 10].

1.1.4 Material of the impeller

This is part of the fluid's viscosity, as the impeller's strength is essential for proper high-speed mixing for a highly viscous fluid. Stirring impellers are most commonly manufactured with stainless steel for laboratory and industrial purposes as that will give durability and corrosion resistance with chemical resistivity. Sometimes PTFE impellers can also be seen in industrial applications where acids or other hazardous chemicals should avoid the metals [7, 8].

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II. MATERIAL AND METHOD

Five different stirrers are used to evaluate the reaction time consumed for layer separation, separation time, and the yield of the process by maintaining other parameters such as the quantity of oil, methanol to oil ratio, amount of catalyst, reaction temperature, and stirring speed. The different blade patterns are used for the experiment, the cross stirrer with four blades connected to the center, the straight stirrer with only two straight blades. Moreover, the blade stirrer, which has a single vertical blade, and the centrifugal stirrer which has two rotatable blades connected to the central shaft. At the same time, the pitched blade stirrer connected to the central shaft with a curved angle was also considered for the experiment.

2.1 Biodiesel Production Process

2.1.1 Pre-treatment

The waste cooking oil (WCO) was filtered with a mesh size of 250 µm to remove any solid contaminants. To ensure complete evaporation of all water molecules, the WCO was heated to 110°C for 10 minutes. The WCO was then allowed to cool to room temperature.

2.1.2 Determination of Acid value and FFA%

The acid value and FFA% were calculated in the manner described by Miyuranga et al. [11], as follows: 1 g of pre-treated WCO was added to a titration flask containing 125 mL isopropyl and 5-6 drops of phenolphthalein as an indicator. Titration with 0.1 M KOH was performed, and the volume required for a colorless solution to turn pale pink was determined (v1). A similar procedure was used for the blank sample devoid of WCO, and the KOH consumption was recorded (v2). The entire titration procedure was done three times to decrease the possibility of human errors. The acid value and FFA content of WCO was then determined using the formulas indicated in (1) and (2) for the acid value and FFA content of WCO, respectively.

$$Acid\ value\ \left(mg\frac{KOH}{g}\right) = \frac{56.1\ \times 0.1\ \times\ (v1 - v2)}{1} \quad (1)$$

$$FFA\,\%\ = \frac{Acid\ value}{2} \quad (2)$$

2.1.2 Transesterification

The transesterification reaction was carried out in a flask with a capacity of 2000 mL. The flask was filled with 1000 mL of pre-treated WCO, included in a stirrer. Transesterification was done with methoxide was created a methanol-catalyst combination. Transesterification was then carried out at a temperature of 25°C using a catalyst of KOH (1 wt.%) of the oil sample in 20 (v / v) of methanol at 600 rpm. Following completion of the reaction, the reaction mixture was allowed to settle until the biodiesel light layer separated from the heavy glycerine layer after 5 minutes of reaction time. The separation of the glycerine and biodiesel layers took approximately three hours. The biodiesel layer known as fatty acid methyl ester (FAME) was isolated by eliminating the glycerine layer. Purification of biodiesel was accomplished by rinsing for 20 minutes with warm distilled water equal to 50% of the volume of biodiesel. The biodiesel was then heated to 110°C for 10 minutes to eliminate any remaining water and unreacted compounds. Washing and drying were carried out until the pH of the biodiesel reached around 7. The proportion of biodiesel produced was computed as shown in (3).

$$Biodiesel\ yield\% = \frac{Biodiesel\ dry\ weight}{WCO\ dry\ weight} \times 100\% \quad (3)$$

2.2 Mixing Apparatus

The mixing behaviors were influenced by multiple parameters such as; the stirrer design (geometry, number of blades, blade angle, rotational direction), stirring speed, the ratio between stirrer blade diameter to reactor inner diameter (d/D), the ratio between reactor bottom to blades and the liquid height (h/H) as given in Figure 1 [12].

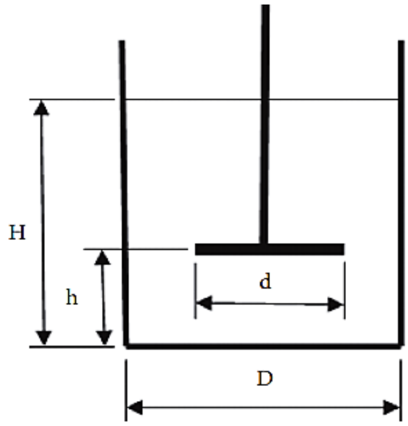

Fig. 1. Dimensions of the Stirrer and the position

Many previous studies have verified that mixing performances vary with the mixing time, the type of impeller used, the number of impeller blades, blade size, working angular speeds, and vessel configurations [13].

To check the mixing effect on biodiesel production, five different blades were used for the experiment, such as cross stirrer (Figure 2a), Straight stirrer (Figure 2b), blade stirrer (Figure 2c), centrifugal stirrer (Figure 2d) and pitched blade stirrer (Figure 2e). The main idea behind the present study was to identify the best blade design for biodiesel production with the highest yield of production. However, in this study, the d/D ratio and the h/H ratio were also studied to evaluate the best performance criteria for industrial-scale biodiesel production.

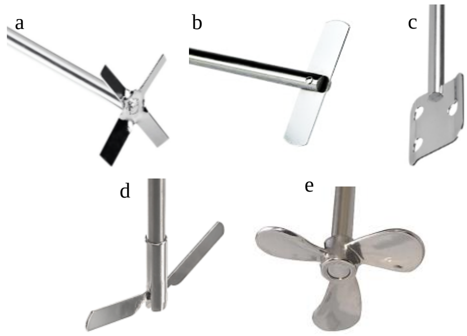

Fig. 2. Blade designs of the impellers used in the experiment. a: cross stirrer; b: Straight stirrer; c: blade stirrer; d: centrifugal stirrer; e: pitched blade stirrer

All five experiments with the parallel were performed by maintaining identical operational conditions, such as; reaction temperature, the rotation speed of the stirrer, the volume of the oil sample, oil to methanol ratio, amount of the catalyst. By maintaining the above parameters, the biodiesel production process is performed to analyze the reaction time needed to get the color changes of the liquid. The reaction conditions are given in Table 1.

TABLE 1. Reaction operating conditions

Parameter	Unit	Value
Oil Volume	L	1
Methanol to Oil ratio	V/V	20%
KOH amount	W/W	1%
Temperature	°C	25
Mixing speed	RPM	600
d/D value		0.3
h/H value		0.3

Then, the reaction mixture was added to the separation funnel for the settling, which required gravity settling for 3-4 hours. Reaction time gives the color changes of the reaction medium, and the settling time was recorded. After two layers were separated, glycerine was discarded, and methyl ester was separated for washing and drying to purify the biodiesel. The produced biodiesel was analyzed for the flashpoint, pH, viscosity, and density compared with the standard biodiesel.

Then based on the yield of the biodiesel production, the best blade design was finalized. After that, the impact of the d/D and the h/H, on the yield were evaluated using the selected blade for the biodiesel process. The d/D was varied by changing the reactor as the blade diameter was fixed. However, the h value, which is the position of the blades from the bottom of the reactor, was varied by keeping the H at a constant value. Table 2 represents the different process conditions performed with the selected blade. Based on the biodiesel yield, the optimum d/D value is selected when h/H is 0.3, and the selected optimum d/D value is used with the h/H value variation for further production with higher efficiency (Table 3).

TABLE 2. d/D variation when h/H = 0.3

Configuration Number	d/D
1	0.2
2	0.3
3	0.4
4	0.6
5	0.8

TABLE 3. h/H variation when d/D = Optimum value

Configuration Number	h/H
1	0.2
2	0.3
3	0.4
4	0.5
5	0.6
6	0.7

III. Results and Discussion

The mixing patterns of the reactor were observed with the different stirrer designs and given in Figure 3, Figure 4, and Figure 5. The radial flow pattern of the fluid occurs when fluid is pushed away from the impeller's axis toward the vessel wall, which is given in Figure 3. The axial flow of the fluid occurs when fluid is pushed up or down along the axis of the impeller (Figure 4). The axial flow direction is decided by the impeller's orientation, which blades are attached, and its agitating direction. The tangential flow pattern of the fluid occurs when fluid is moved horizontally around the vessel as with a paddle (Figure 5).

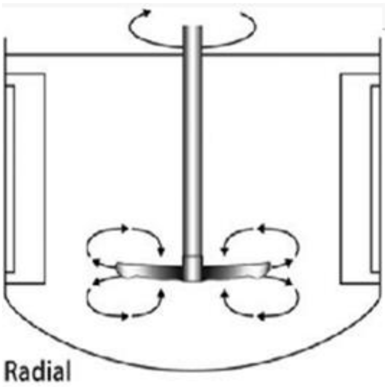

Fig. 3. Radial Flow of the impeller

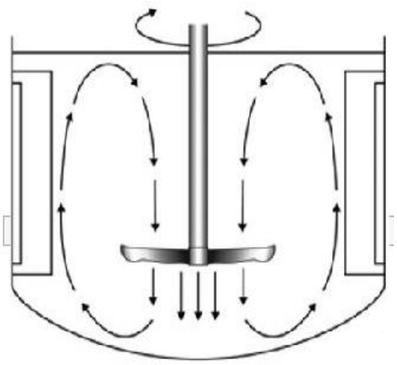
Fig. 4. Axial Flow of the impeller

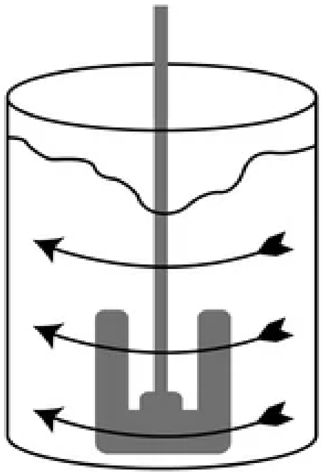
Fig. 5. Tangential Flow of the impeller

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It should be noted that axial flow impellers are essential in mixing solid-liquid suspensions because they prevent the solid from settling at the bottom of the reactor. The radial flow impellers should be used in situations where high shear rates are needed for the process, such as dispersion processes. Moreover, Tangential flow impellers are essential for mixing high viscous fluid. Therefore, it should be noted that axial flow impellers are the best impellers for biodiesel production as they should adequately mix the raw materials and the catalyst for a better reaction. Otherwise, the catalyst will deposit at the bottom of the reactor with the glycerine and terminate the reaction. The results of the measured parameters are given in Table 4. At the same time, the flow pattern of the fluid is closely analyzed to determine the flow, whether axial or radial. The identified flow pattern is also tabulated in Table 5.

With the different stirrer arrangements, biodiesel was produced to analyze the yield of the process. The washed and dried sample yield was calculated, as well as the physical properties such as viscosity, density, flash point, pH, and FFA% were also measured. The highest yield of 96.4 was achieved with a Pitched blade stirrer followed by a centrifugal stirrer of 94.1. Both Centrifugal and Pitched blade stirrers give the Axial flow pattern during the mixing process (Table 4). However, other stirrers also give a higher yield with the present condition. The viscosity, flash point, density, and FFA% were within the acceptable range of ASTM standards. However, the lowest viscosity of the biodiesel sample was obtained with the pitched blade stirrer. For a high-quality fuel, a lower value of viscosity is better as that will flow smoothly without clogging the internal lines in the engine.

TABLE 4. Measured parameters of the biodiesel samples

Properties of the biodiesel	Cross Stirrer	Straight Stirrer	Blade Stirrer	Centrifugal Stirrer	Pitched blade Stirrer
Reaction time, min	30min	30min	30min	30min	30min
Settling time, hours	4 hours	4 hours	4 hours	4 hours	4 hours
Yield, %	86.4	88.2	86.5	94.1	96.4
FFA%	1.2	1.3	1.3	1.3	1.2
pH	7.03	7.02	7.07	7.05	7.08
Density, kg/m3	880	882	881	875	870
Viscosity,	4.1	3.5	3.8	3.9	3.2
Flash point, °C	152	151	158	150	155

TABLE 5. Observed flow pattern with the different stirrer design

Blade Design	Flow Pattern
Cross Stirrer	Radial
Straight Stirrer	Radial
Blade Stirrer	Radial/ Tangential
Centrifugal Stirrer	Axial/Radial
Pitched blade stirrer	Axial

Radial flow pattern observed with a cross stirrer, and straight stirrer, while blade stirrer shows radial or tangential flow pattern. Centrifugal stirrer shows axial flow pattern and sometimes radial flow during the reaction. The pitched blade stirrer shows an axial flow pattern during the reaction. The pitched blade stirrer creates minimum vortex height among other stirrers when maintaining d/D and the h/H at constant values (Figure 6). Therefore, a pitched blade stirrer was selected to analyze the impact of d/D and h/H ratios on the biodiesel production process. The highest yield also was obtained for pitched blade operation. The reason for that may be the proper axial mixing during the production process, as that will not let the catalyst settle at the bottom of the reactor.

Fig. 6. Vortex formation with pitched blade stirrer

The biodiesel yield was analyzed for different d/D and h/H values and given in Figure 7 and Figure 8 for selected stirrer based on the axial flow formation.

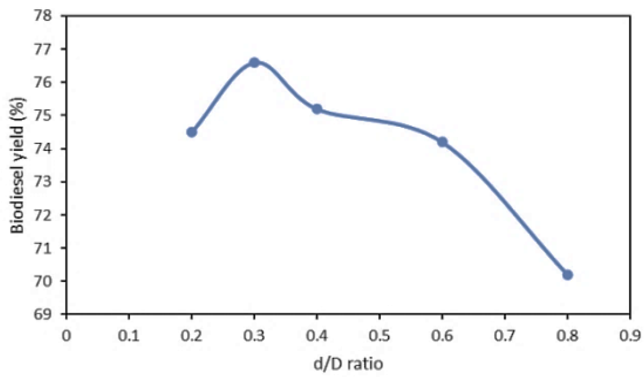

Fig. 7. Yield of the biodiesel variation with the d/D when Pitched blade stirrer attached

When increasing the d/D value by keeping the h/H value at 0.3, the biodiesel yields gradually increased up to a specific limit and started to decrease again. Then the optimum yield of 98.0 was selected as the highest biodiesel production, and the 0.4 value of d/D was chosen as the optimum d/D ratio (Figure 7).

The selected optimum d/D value of 0.3 was used for the h/H optimization (Figure 8). The highest yield of 98.0 was achieved when h/H was 0.4. Therefore, optimum h/H is considered the 0.4 for biodiesel production with the Pitched blade stirrer.

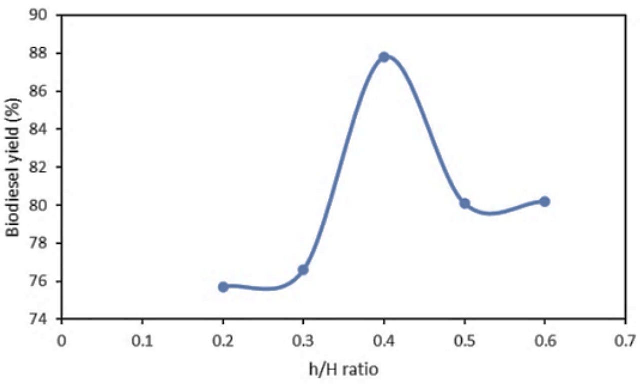

Fig. 8. Vortex height variation of the biodiesel sample with h/H

I. CONCLUSION

The setup obtained the highest yield with a pitched blade stirrer. The properties of the biodiesel are with the ASTM standards. The flow patterns of all five stirrers were observed and identified. The pitched blade stirrer gives an Axial flow pattern while Cross, Blade, and Straight stirrers show radial flow patterns. The centrifugal stirrer has shown radial and an axial flow pattern which was challenging to identify precisely as radial or axial. The axial flow should be there for biodiesel transesterification to avoid solid catalyst deposition at the bottom of the reactor. Therefore, the experiment proved a theoretical explanation of axial flow mixing requirements is valid for the alkaline esterification of biodiesel production process as well.

Moreover, d/D, which is blade diameter to reactor diameter ratio, and h/H, which is the ratio of the height of the bottom of the reactor to the location of the blade to fluid height, was optimized. The optimum d/D and h/H were 0.3 and 0.4 achieved for the highest biodiesel yield. Therefore, it can be concluded that the Pitched blade stirrer with d/D 0.3 and h/H 0.4 are the most suitable parameters for transesterification reaction to obtain the highest yield.

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