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Research Paper

Design, Fabrication, and Assessment of a Hydrodynamic Reactor for Biodiesel Production

Kimia Taki[1], Bahram Hosseinzadeh Samani[1*]
[1]Department of Mechanical Engineering of Biosystem, Shahrekord University, Shahrekord, Iran
[*]Email of corresponding author: b.hosseinzadehsamani@gmail.com
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Abstract
Biodiesel is a bio-renewable fuel derived from vegetable oils and animal fats with less environmental pollution than fossil fuels. This research aims to design, fabricate, and evaluate a hydrodynamic reactor for biodiesel production. According to the fluid characteristic, the rotor and stator were designed and the electric engine was chosen. The cavities of the rotor were designed for optimal cavitation. The effect of reaction time and rotational speed were examined to assess the reactor. Speed rotor rotational speed of hydrodynamic cavitation reactors can intensify the transesterification reaction by increasing the occurrence of cavitation in the space between the rotor and the stator. Therefore, to investigate the effect of this variable on biodiesel production efficiency, three levels were selected (2000, 2500, and 3000 rpm). As the rotational speed of the hydrodynamic reactor increases, the cavitation operation increases, and as a result, the conversion percentage rises too. This experiment indicated that the rise of residence time from 30 s to 60 s increases methyl esters yield, but following the time up to 60 s, the methyl esters yield has no significant changes. The results showed that the biodiesel produced from waste oil in the hydrodynamic reactor could be a suitable alternative to diesel.

Keywords
Hydrodynamic Reactor, Reactor Fabrication, Biodiesel, Cavitation

1. Introduction
In recent years due to declining fossil fuels and rising global temperatures, renewable energy, including wind, solar, and biomass, has been received increasing attention; among them, bioethanol or biodiesel derived from bio-feedstock are the sustainable, economical, and alternative energy source for fossil fuels [1]. A high percentage of our daily energy comes from fossil fuels (such as home heating, lighting, moving appliances, and cars). One renewable energy source that replaces fossil fuels is biodiesel [2]. Biodiesel is one of the most suitable biofuels that can be a good alternative to conventional liquid fuels such as diesel. Biodiesel is a highly effective alternative fuel used in different parts of transportation worldwide, such as those in the United States, Canada, Australia, Japan, China, and other Asian countries [3, 4]. It is a renewable, biodegradable, and non-toxic fuel for compaction-based IC engines, the monoalkyl esters of long-chain fatty acids derived from vegetable oil and animal fats [5]. In addition to the benefits of using biodiesel fuel, this fuel also has limitations, the most important of which is the high cost of production [6, 7]. Higher feedstock costs, reaction rates, and reaction times cause biodiesel production costs to be almost twice as high as oil-

based diesel fuel [6-8]. Generally, the viscosity of vegetable and animal oils is another problem of their direct use in diesel engines [9-11]. Biodiesel is mainly obtained by transesterification (alcoholysis) of oil and alcohol (mostly methanol) in the presence of a catalyst [12]. Indeed, the use of biodiesel fuel, whether pure or mixed with diesel fuel, does not significantly affect the thermal efficiency of diesel engines. Some technologies have been developed and used to improve agitation and heat transfer in recent years. These technologies have led to the design and create new reactors that will increase the reaction rate and reduce reaction time.

Process intensification is defined as strategies used to reduce process, minimize investment costs, improve process safety, improve production and energy efficiency, and increase product quality [13]. There are different methods for producing biodiesel by transesterification, especially in recent years; scientists and chemical engineers have found that sonochemical methods are suitable solutions for bottlenecks in chemical processes [14]. Sonochemical effects arise from the action of ultrasound (US) waves and hydrodynamic Cavitation (HC) [15]. Cavities are generated when the local pressure falls below the fluid's vapor pressure; cavitation may also lead to a localized increase in temperature at the phase boundary, enhancing the transesterification reaction [15-18]. In other words, the turbulence intensity created on the micro-level by the holes in the hydrodynamic reactor causes a difference in point pressure and the collapse of bubbles that effectively eliminates the mass transfer resistance during the reaction [19, 20]. This work aims to design and fabricate a hydrodynamic cavitation reactor to produce biodiesel from waste oil.

2. Materials and methods

2.1 Design of hydrodynamic cavitation reactor

This study aims to design and fabricate a hydrodynamic reactor for biodiesel production. This reactor consists of a rotor and stator; The hydrodynamic system is used to spin the fluid at high speed. Rotation of the rotor is an important factor in increasing the agitation intensity and improving the transesterification reaction rate. Also, because the highest energy consumption of the system occurs in the reaction unit of the system, the design and selection of the appropriate torque generator and power are important.

$$T_T = T_r + T_a \qquad (1)$$

T_T is the total torque required (N.m), T_r is torque caused by the reacting fluid (N.m), and T_a is Starting torque due to inertia of rotating components (N.m).

The Tr is calculated using the fluid passage relations between two concentric cylinders. Figure 1 shows the fluid flow between two concentric and rotating cylinders .

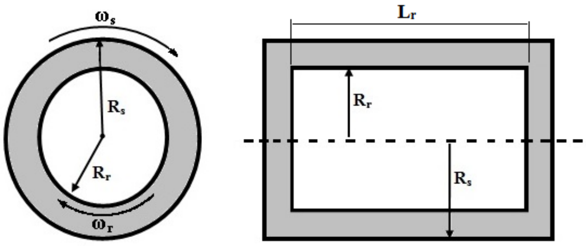

Figure 1. Fluid flow between two concentric and rotating cylinders

Tangential shear stress due to the passage of fluid through two concentric and rotating cylinders is calculated from Eq. 2.

$$\tau_r = \frac{2\mu(\omega_s - \omega_r)}{R_s^2 - R_r^2} \times \frac{R_s^2 \times R_r^2}{R^2} \qquad (2)$$

τ_r is shear stress (pa.s), μ is dynamic fluid viscosity (pa.s), R_r is rotor radius (m), R_s is stator radius (m), R is the radius of space between two cylinders (m), ω_r is the angular speed of the rotor (rad/s), ω_s is the angular speed of the stator (rad/s).

According to Eq. 2, the shear stress for the tangent fluid on the rotor surface is calculated from Eq. 3.

$$\tau_r(R = R_r) = \frac{2\mu R_r^2(\omega_s - \omega_r)}{R_s^2 - R_r^2} \qquad (3)$$

Because the stator is fixed in the hydrodynamic reactor ($\omega_s = 0$) and only the rotor rotates, Eq. 4 is also used to calculate the shear stress.

$$\tau_r = \frac{F}{A} \qquad (4)$$

F is the shear force (N), and A is the cross-sectional area (m^2).

Eq. 5 shows the transfer torque from rotor to fluid

$$T_r = F \times R_s \qquad (5)$$

$$T_r = \tau_r \times A \times R_s \qquad (6)$$

After inserting the values of cross-sectional area ($A = 2\pi R_s L$) and shear stress, Eq. 7 is obtained to calculate the transfer torque from rotor to fluid.

$$T_r = 4\pi\mu L \times \frac{R_r^2 \times R_s^2}{R_s^2 - R_r^2} \times \omega_r \qquad (7)$$

According to Eq. 6, a fluid's dynamic viscosity (μ) is one of the most important parameters determining T_r.

In this study, Eq. 7 was used to calculate the dynamic viscosity of the mixed fluid.

$$\mu_{mix} = \rho_{mix} \times \vartheta_{mix} \qquad (8)$$

μ_{mix} is the dynamic viscosity of mixed fluid (pa.s), ρ_{mix} is the density of the mixed fluid (kg/m^3) and ϑ_{mix} is the kinematic viscosity of the mixture (m^2/s).
In this research, to calculate the kinematic viscosity of the mixture, the refutes method has been used on a volume basis (Maples, 2000). This method consists of the following three steps.
Step 1: Determine the Viscosity blending Index (VBI) of each fluid that make the mixture. Eq. 9.

$$VBI_i = \frac{\ln \vartheta_i}{\ln(1000 \times \vartheta_i)} \qquad (9)$$

VBI is the viscosity blending index and ϑ_i is the kinematic viscosity of the mixture (Cst).

Table1. Physical properties of waste oils and methanol

Properties	Waste oil	Methanol
Density (gr/lit)	920	792
Dynamic viscosity (pa.s)	0.04	0.0005
Kinematic viscosity (Cst)	5.34	6.86
Molar mass (g/mol)	876	32.08

According to Eq. 9 and Table 1, the viscosity blending index of waste oil and methanol was calculated.

$$VBI_{oil} = \frac{\ln \vartheta_{oil}}{\ln(1000 \times \vartheta_{oil})} = \frac{\ln 5.34}{\ln(1000 \times 5.34)} = 0.36$$

$$VBI_{meth} = \frac{\ln \vartheta_{meth}}{\ln(1000 \times \vartheta_{meth})} = \frac{\ln 6.86}{\ln(1000 \times 6.86)} = -0.05$$

Step 2: determining viscosity blending index (VBI $_{mix}$)

$$VBI_{mix} = \sum_{i=0}^{n} V_i \times VBI_i \qquad (10)$$

VBI is the viscosity blending index, and V_i is the volume fraction of each fluid (%).
Increasing methanol reduces the dynamic viscosity of the mixture. Therefore, to calculate the maximum torque from oil and methanol mixtures, molar ratios of 4:1, 6:1, and 8:1 ratio were selected.
According to Eq.10 and the molar ratio chosen (4:1), the VBI $_{mix}$ was calculated.

$$VBI_{mix} = \sum_{i=0}^{n} V_i \times VBI_i = (V_{oil} \times VBI_{oil}) + (V_{meth} \times VBI_{meth}) = 0.28 \qquad (11)$$

Step 3: determining the kinematic viscosity of the mixture.

$$\vartheta_{mix} = EXP\left(\frac{\ln(1000)\times VBI_{mix}}{1-VBI_{mix}}\right) = EXP\left(\frac{\ln(1000)\times 0.28}{1-0.28}\right) = 14.7(Cst) \qquad (12)$$

The density of the fluid mixture was obtained using Eq.13.

$$\rho_{mix} = \sum_{i=1}^{n}(V_i \times \rho_i) \qquad (13)$$

By substituting the volumetric percentages of oil and methanol in a ratio of 4: 1, which are 0.79 and 0.14, respectively, the fluid density of the mixture was calculated at 847.70 gr /lit. As a result, the dynamic viscosity of the mixture fluid was estimated at 0.013 (pa.s).

Table 2. Geometric dimensions of rotor and stator

Geometric dimensions	rotor	Stator
Length (m)	0.08	0.09
Radius (m)	0.09	0.097

According to Table 2, T_r was obtained.

$$T_r = 4\pi\mu_{mix}L \times \frac{R_r^2 R_s^2}{R_s^2 - R_r^2} \times \omega_r = 4 \times 3.14 \times 0.013 \times 0.08 \times \frac{0.09^2 \times 0.097^2}{0.097^2 - 0.09^2} \times 314.15 = 0.24(n.m)$$

(14)

$$\omega_r = 3000rpm = 314.15rad/s$$

The starting torque was calculated from Eq.15 in this study.

$$T_a = J_t a = J_t \times \frac{\omega_{max} - \omega_0}{t} \qquad (15)$$

J_t is the inertia of all rotating components (kg.m^2), a is angular acceleration (rad/s^2), ω_{max} is maximum angular velocity and ω_0 initial angular velocity.
Eq. 16 was used to calculate the inertia of the components used.

$$J = \frac{1}{8} m_L D_L^2 = \frac{\pi}{32}\rho_L L_L D_L^4 \qquad (16)$$

J is the inertia of mechanical load (kg.m^2), m_L is mechanical load mass (kg), D_L mechanical load diameter (m), ρ_L mechanical load density (kg/m^3) and L_L is mechanical load length (m).

Table 3. Specifications of rotating components and inertial of each component

Rotating piece	Material	Density (g/lit)	Diameter (m)	Length (m)	Number	Inertia (kg.m^2)
Rotor	Polypropylene	905	0.18	0.08	1	0.007
Shaft	Steel	7850	0.025	0.215	1	0.000064

After calculating the inertia of each rotating component, the total inertia was also calculated from Eq. 17.

$$J_T = J_R + J_{sh} \qquad (17)$$

J_T is the inertia of all rotating components (kg.m^2), J_R is Reactor rotor inertia, and J_{sh} is shaft inertia (kg.m^2). After calculations, the J_T was calculated at 0.0075 kg.m^{2,} and the time required to reach maximum speed was considered 1 sec; finally, the starting torque was estimated at 2.36 N.m. The total torque needed for the reaction unit was calculated.

$$T_T = T_r + T_a = 0.24 + 2.36 = 2.60\ (n.m)$$

The maximum power required for the rotating rotor inside the stator, Eq.18, was used to calculate.

$$P_T = \frac{T_T \times N}{9550} = \frac{2.60 \times 3000}{9550} = 0.81(kw) \qquad (18)$$

P_T is Maximum rotational power (kW), N rotor rotational speed (rpm).

2.2 Experimental equipment

This research aims to design and fabricate the hydrodynamic reactor for biodiesel production, which has the following main components: 1-Rotor, 2-Stator, 3-Peristaltic pump, 4-Electro-Motor and 5-Connector pipes

The rotor is made of stainless steel and has holes that produce bubbles or holes by its edge, and the stator is considered transparent to observe the reaction; for this purpose, polycarbonate is selected to evaluate its heat and friction resistance properties for fluid movement. In this reactor, an electromotor is used to supply the driving force of the rotor. The electromotor used in this system was a Ronix gearbox motor with a power of 750 W and a speed of 3200 rpm.

2.3 Transesterification of waste oil in hydrodynamic cavitation reactor

This study used waste oil, methanol of 99% purity, and potassium hydroxide of 98% purity (Merck, Germany) in the transesterification reaction. First, the oil must be prepared to experiment. This preparation is often unnecessary for fresh oils because the amount of water and additional material (such as food cuts and any other material) is very low. The waste oil was filtered and settled in a container to remove different materials in this experiment. After preparing the waste oil, the oil reacts in the presence of methoxide and leads to biodiesel and glycerin production. Methoxide is a mixture of methanol with potassium hydroxide (KOH). The catalyst is added to the alcohol and dissolved by using a magnetic stirrer to increase the reactivity and solubility of the catalyst to prepare methoxide. Then the oil drilled in the previous step was slightly warmed and added to methoxide. At this stage, the reactant mixture was pumped into the hydrodynamic reactor and entered into the space between rotor and stator. As the rotor rotates at speeds between 1000 and 3000 rpm, the fluid circulates between the rotor by centrifugal force. The holes on the rotor cause changes in pressure and intensification of the shear force. As a result, cavitation occurs. The rotation of the liquid rapidly increases the pressure and temperature and causes the bubbles to burst, resulting in the formation of glycerin and methyl esters and some excess alcohol. PerkinElmer-Clarus 580 gas chromatograph (made in USA) was used in this study, set according to BS EN 14103 standard to calculate the biodiesel conversion percentage and biodiesel efficiency. Responses were issued by the detector, which is the result of preparing and injecting the sample into a gas chromatograph. Chromatograms resulting from detector responses are observed, and calculations are performed using Total Chrome software. Reaction performance measures the amount of oil converted to biodiesel and the amount of unreacted oil.

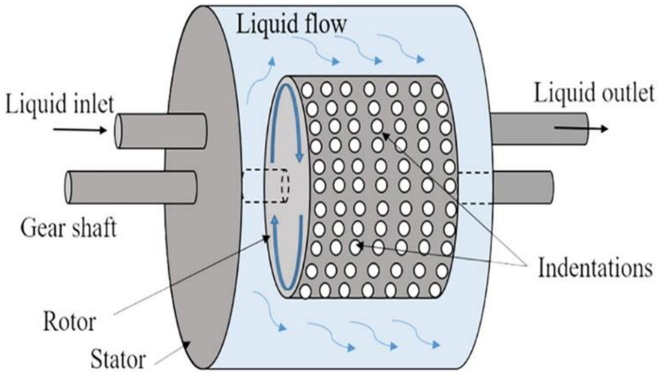

Figure 2. Schematic of the rotor and stator inside the hydrodynamic reactor

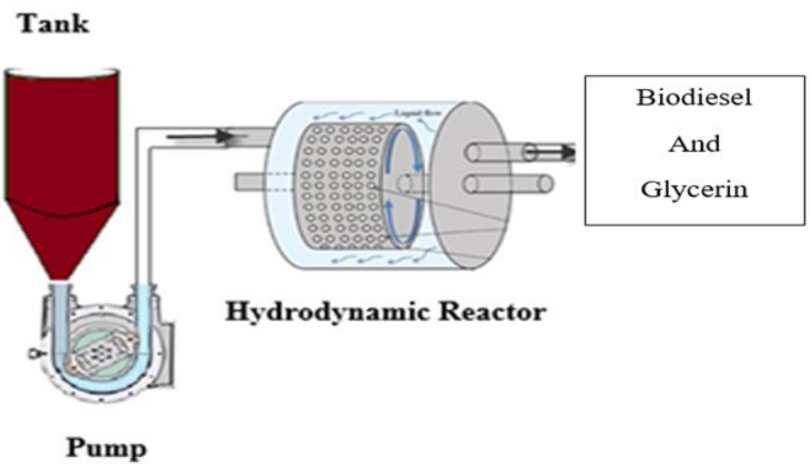

Figure 3. The Schematic of the set-up for the hydrodynamic-assisted biodiesel production process

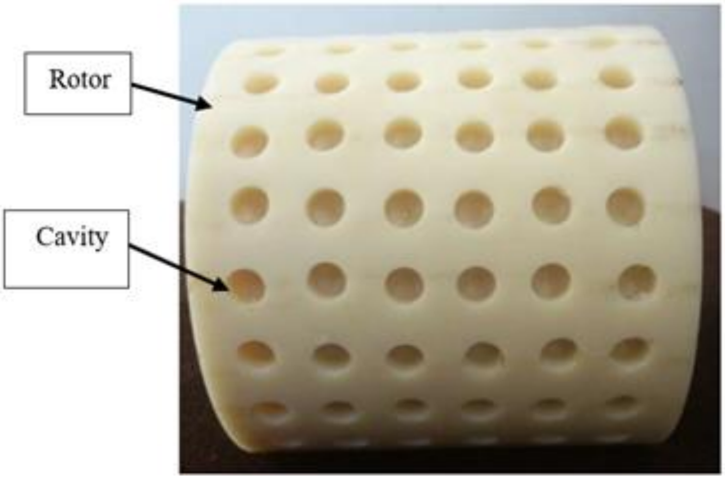

Figure 4. Rotor and cavities

2.4 Statistical Analysis

In this research LSD method was used, this experiment was performed in three replications, and two independent variables, such as residence time and rotational speed, were examined.

3. Evaluation of hydrodynamic cavitation reactor

3.1 Investigation of reaction time in the hydrodynamic system

Rotor rotational speed of hydrodynamic cavitation reactors can intensify the transesterification reaction by increasing the occurrence of cavitation in the space between the rotor and the stator. Therefore, to investigate the effect of this variable on biodiesel production efficiency, three levels were selected (2000, 2500, and 3000 rpm). As the rotational speed of the hydrodynamic reactor increases, the cavitation operation increases, and as a result, the conversion percentage rises too. As is shown in Figure 5, The trend of production efficiency graphs shows that in the range of lower speeds (2000-2500 rpm), production efficiency is higher in longer residence times. While in the range of higher rotational speeds (2500-3000 rpm), production efficiency has increased at shorter residence times than longer residence times. It is due to the reversibility of the transesterification reaction. At 30 seconds, the production efficiency is higher at a rotational speed of 3000 rpm. It means that more cavitation and stirring occur at higher rotational speeds in less time. At 60 seconds, the speed graphs of 2000 and 2500 rpm, are close to each other, and there is no significant difference in production efficiency. At 90 seconds, production efficiency has decreased at all three levels (2000, 2500, and 3000 rpm), and the values are very close to each other, which indicates the equilibrium and reversibility of the transesterification reaction [19, 21-23].

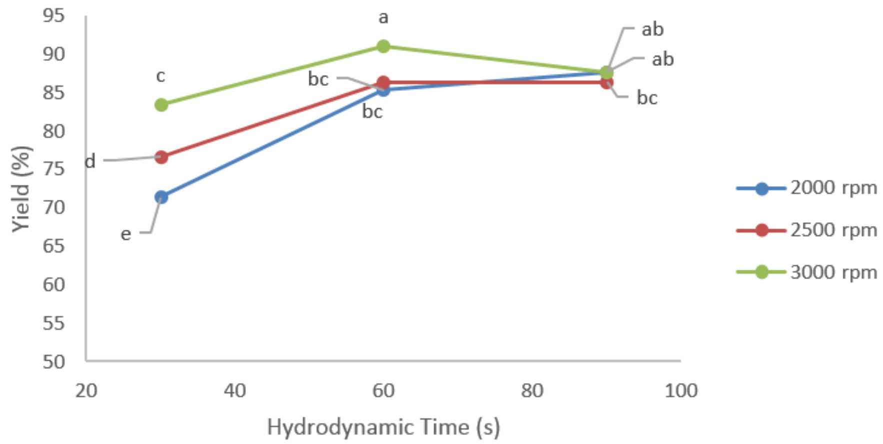

Figure 5. Effects of reaction time on methyl ester content in the hydrodynamic reactor

After washing and purifying the produced biodiesel, several important properties were measured based on ASTM D6751. The results showed that all the properties of methyl ester comply with biodiesel standards. Therefore, biodiesel produced from waste oil in the hydrodynamic reactor could be a potential alternative to diesel. Table 4.

Table 4. The Produced Biodiesel in hydrodynamic reactor Properties compared to the ASTM D6751 standard.

Property	**Test Method**	**Limits**	**Units**	**Measured Property**
Water and Sediment	ASTMD2709	0.05max	%volume	0.04
Kinematic Viscosity at 40°C	ASTMD445	1.9-6.0	mm^2/s	3.9
Sulfated Ash	ASTMD874	0.02max	%mass	0.017
Methanol Content	EN14110	0.20max	%volume	0.19
Carbon Residue	ASTMD4530	0.05max	%mass	0.08
Acid Number	ASTMD664	0.50max	mgKOH/g	0.12
Free Glycerin	ASTMD6584	0.02	%mass	0.051
Total Glycerin	ASTMD6584	0.24	%mass	0.29
Oxidative Stability	EN14112	3min	Hours	2.8

3.2 Comparison of the conventional method with the hydrodynamic method

As it is shown in Figure 6, the reaction time in a hydrodynamic reactor is shorter than in the conventional method. It was observed that 91% conversion was obtained in 2.5 minutes, which indicates the highest conversion percentage in this reactor. Compared to the conventional method, the highest conversion percentage was obtained, 91%, in 80 minutes in similar conditions. Therefore, it can be concluded that the hydrodynamic reactor significantly increases the conversion percentage of biodiesel production in a short time compared to the conventional method [24] also reported similar results.

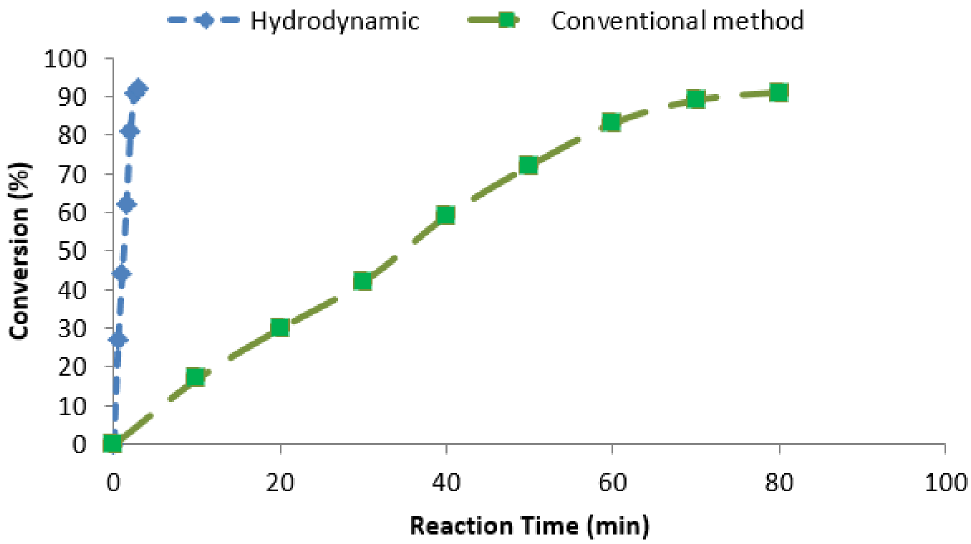

Figure 6. Comparison of conventional method with hydrodynamic cavitation method

4. Conclusion

The presented work has shown the potential of the hydrodynamic reactor for biodiesel production from waste oil in the presence of KOH and methanol. This study aims to design and fabricate a hydrodynamic reactor. This reactor consists of a rotor and stator; The hydrodynamic system is used to spin the fluid at high speed. Rotation of the rotor is an important factor in increasing the agitation intensity and improving the transesterification reaction rate. The results showed that by increasing the rotational speed of the reactor, the cavitation increases, and the conversion percentage increases. Results showed that by increasing the reaction time from the 30s to 60s, methyl ester content increases, but up to 60s, there are no significant conversion percentage changes. The hydrodynamic reactor achieved the highest production efficiency at two-speed levels of 2000 and 3000 rpm in 90 seconds at 87.66% (Yield). According to these results, transesterification of waste oil in a hydrodynamic cavitation reactor could function as a good alternative to diesel.

5. Acknowledgment

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