บทคัดย่อ

รหัสโครงการ: MRG5908141

ชื่อโครงการ:การผลิตไบโอดีเซลจากน้ำมันพืชใช้แล้วด้วยปฏิกิริยาทรานซ์เอสเทอริฟิเคชันในเครื่องปฏิกรณ์แบบประยุกต์

ชื่อนักวิจัย และสถาบัน ดร. วีรินทร์ดา อัปมานะ มหาวิทยาลัยเทคโนโลยีราชมงคลธัญบุรี

อีเมล์: weerinda.a@en.rmutt.ac.th

ระยะเวลาโครงการ: 2 ปี

บทคัดย่อ:

งานวิจัยนี้ศึกษาการผลิตไบโอดีเซลจากน้ำมันปาล์มและน้ำมันพืชที่ใช้แล้วโดยใช้เครื่องปฏิกรณ์แบบจานหมุน (Spinning disc reactor, SDR) ผ่านปฏิกิริยาทรานส์เอสเทอริฟิเคชัน โดยใช้ตัวเร่งปฏิกิริยาเป็นโซเดียมไฮดรอกไซด์ ซึ่งหาสภาวะที่เหมาะสมในการผลิตไบโอดีเซล โดยแปรผันตัวแปรต่าง ๆ ที่มีผลต่อค่าร้อยละผลได้ไบโอดีเซล ได้แก่ ชนิดของแอลกอฮอล์ อุณหภูมิในการทำปฏิกิริยา อัตราส่วนระหว่างเมทานอลต่อน้ำมันปาล์ม ปริมาณตัวเร่งปฏิกิริยา ความเร็วรอบของจานหมุน และระยะห่างระหว่างจานหมุน ผลการศึกษาพบว่า ร้อยละผลได้เมทิลเอสเทอร์สูงถึง 97.0 และ 91.0 ที่เวลาที่สารอยู่ในเครื่องปฏิกรณ์เพียง 2-3 วินาที เมื่อใช้สารตั้งต้นเป็นน้ำมันปาล์มและน้ำมันพืชที่ใช้แล้ว ตามลำดับ ที่สภาวะอัตราส่วนระหว่างเมทานอลต่อน้ำมันปาล์มเท่ากับ 6 ปริมาณตัวเร่งปฏิกิริยาโซเดียวไฮดรอกไซด์ร้อยละ 1.0 โดยน้ำหนัก ความเร็วรอบจานหมุน 1000 รอบต่อนาที และอุณหภูมิในการทำปฏิกิริยาเท่ากับ 60 องศาเซลเซียส ในขณะที่เครื่องปฏิกรณ์แบบทั่วไปหรือกวนเชิงกลใช้เวลาที่สารอยู่ในเครื่องปฏิกรณ์สูงถึง 90 นาที จากการศึกษาจลนพลศาสตร์อันดับของการเกิดปฏิกิริยาคืออันดับหนึ่ง มีค่าคงที่การเกิดปฏิกิริยาสูงกว่าการใช้เครื่องปฏิกรณ์แบบกวนเชิงกลถึง 20000 เท่า และมีพลังงานก่อกัมมันต์เท่ากับ 57.5 และ 43.4 kJ/mol เมื่อใช้สารตั้งต้นเป็นน้ำมันปาล์มและน้ำมันพืชที่ใช้แล้วนอกจากนี้เปรียบเทียบประสิทธิภาพผลได้ในการผลิตไบโอดีเซลด้วยเครื่องปฏิกรณ์ชนิดอื่นๆ เช่น แบบกวนเชิงกล อัตราโซนิค และไฮโดรไดนามิคคาวิเทชั่น พบว่าการใช้ SDR เพิ่มประสิทธิภาพผลได้ในการผลิตไบโอดีเซลได้สูงมาก ดังนั้นเครื่องปฏิกรณ์แบบจานหมุนเป็นเทคโนโลยีที่จะพัฒนาไปสู่การผลิตไบโอดีเซลแบบต่อเนื่องได้

คำหลัก : เครื่องปฏิกรณ์แบบจานหมุน ไบโอดีเซล น้ำมันพืชที่ใช้แล้ว เวลาที่สารอยู่ในเครื่องปฏิกรณ์

Abstract

Project Code : MRG5908141

Project Title : Biodiesel synthesis from waste cooking oil via transesterification reaction using a spinning disk reactor

Investigator : Dr. Weerinda Appamana , Rajamangala University of Technology Thanyaburi

E-mail Address : weerinda.a@en.rmutt.ac.th

Project Period : 2 years

Abstract:

A spinning disc reactor (SDR) was investigated as a process intensification technology for continuous biodiesel production. Refined palm oil (RPO) and waste cooking oil (WCO) were transesterified with methanol or ethanol in the presence of NaOH homogeneous catalyst. The effects of type of alcohol, operating temperature, methanol to oil molar ratio, catalyst loading, rotational speed and the gab distance between discs were investigated. The highest FAME yields as high as 97.0% and 91.0% could be achieved at a very short residence time of 2-3 seconds when using RPO and WCO, respectively, as the reactant at a molar ratio of 6, NaOH concentration of 1.0 wt%, temperature of 60 °C, flow rate of 260 mL/min, and rotational speed of 1000 rpm. The use of SDR obviously offers a significant reduction in the reaction time for the transesterification especially when compared with the reaction time of 90 min required for the conventional mechanical stirrer. The reaction rate constant obtained in SDR was found to be about 20,000 fold higher than that of MS (only 0.031 min^{-1}). The calculated values of activation energy based on the first order reaction kinetics were 57.5 and 43.4 kJ/mol for RPO and WCO, respectively, which were lower than those reported in the cases using other types of mixing (hydrodynamic cavitation, ultrasonic and mechanical stirrer). The performance of SDR in term of yield efficiency was also compared with other reactors. It was clearly demonstrated that SDR is the most promising intensification reactor for continuous biodiesel production.

Keywords : Spinning disc reactor (SDR), biodiesel, waste cooking oil, residence time

2. Executive summary

Due to the limited fossil resources and environment problems caused by the combustion of fossil fuels, there was demand to find alternative energy sources to meet the increasing world energy needs. Many types of renewable energy especially, biodiesel has been concerned due to its reliable on the environmental-friendly, sustainability and high heating values as nearly equivalent to diesel fuels. Normally, 95% of world biodiesel production is derived from edible oils. Consumption of edible oil in biodiesel production has led to the prices of edible oil and biodiesel to increase to levels 1.5 fold higher than diesel fuel. For this reason, non-edible waste cooking oils become more attractive feed stocks for minimizing the total cost. Waste cooking oil is considerably cheaper five times average lower than refined cooking oil. Furthermore, utilization of waste cooking oil as a feed stock of biodiesel provides an alternative route for its disposal in a more sustainable and environmental-friendly way.

Generally, commercial biodiesel is produced via transesterification, which transforms triglyceride and methanol into fatty acid methyl esters (FAMEs) in the presence of alkaline or acid catalyst with glycerin as a byproduct. However, some problems are associated with biodiesel production process. First, conventional reactors for biodiesel production are typically operated in batch mode, which involves intensive labor and high cost, yielding poor production efficiency. Therefore, a continuous production process is preferred by industry. In 2011, Santacesaria et al. performed continuous transesterification of soybean oil with methanol using a tubular reactor filled with small spheres of potassium hydroxide (KOH) as the catalyst. Experimental results showed that a yield of methyl esters of 97.3% can be achieved with a residence time of 60 min. To produce biodiesel from Karanja oil and methanol with KOH as the catalyst, Agarwal et al. utilized a helical tube reactor, a maximum conversion of 92.6% was achieved with a rather short residence time of 4 min.

Another limitation of current biodiesel production is the significant mass transfer resistance between two reactants (alcohol and triglycerides) which are immiscible with each other. Consequently, reaction time is usually long when biodiesel is produced in a conventional stirred tank due to its low mixing and mass transfer efficiency. High-speed stirring is generally used to improve the contact between the two phases. This consumes a great deal of energy, and it is not an efficient way of contacting the two phases. Therefore, there are a large number of researches proposing efficient reactors to solve the problems as mentioned above. Spinning disk reactor (SDR) is one of the interesting technologies employing high gravity fields. The concept has been shown as appropriate for fast and very fast liquid/liquid reactions involving large heat effects, such as polymerizations, synthesis of pharmaceutical products, and fine particle production. In 2006, Chen et al. reported that a spinning disk reactor (SDR) provided the highest mixing efficiency among several mixing devices, including a continuous flow stirring reactor, a static mixer, an ultrasound-assisted flow cell, and a rotating packed bed. An SDR consists of a rotating disk within a stationary housing. The liquid enters at the disk center and flows rapidly outward as thin films on the disk surface. The SDR is used for polymerization and production of micro- or nanoparticles by precipitation because of its remarkable micro-mixing efficiency. In 2006, Boodhoo et al. studied cationic polymerization of styrene in an SDR, it can use a higher monomer concentration and higher reaction temperature because an SDR has excellent heat transfer efficiency. Silver nanoparticles were synthesized in an SDR by Tai et al. Increasing micro-mixing intensity reduced particle size. Transesterification of canola oil with methanol in an intensified spinning disk reactor was investigated by Qiu et al. Conversion was related to the rotational speed, feed flow rate, and surface topology of the disk. Conversion was about 87% at a rotational speed of 1000 rpm and reaction temperature of 60 °C with a very short residence time (<1 s). By applying this technique, high yield of biodiesel was obtained in a short reaction time. Under this operation, transesterification can be carried out at low temperature and less amount of catalysts and methanol are required which are considered as advantages of this reactor. Many researchers have proposed using homogeneous catalysts in a SDR such as potassium hydroxide and sodium hydroxide. The widely used alkaline catalysts are NaOH and KOH. Keera et al. reported that the transesterification of cottonseed oil and methanol using 1 wt% amount of NaOH catalyst, biodiesel yield of 97% could be achieved within 60 min at 60 ^{o}C with a methanol/oil molar ratio of 6.

In this work, an SDR will be employed as the reactor for continuous biodiesel production. Transesterification of waste cooking oils with methanol using NaOH as a catalyst will be investigated in the SDR. Experimental conditions, such as the methanol to-oil molar ratio, catalyst concentration, reaction temperature, rotational speed, and flow rate as well as reactor configuration will be varied. The yield and production rate of biodiesel obtained in this SDR will be compared to those obtained in other reactors to gain more understanding about the effect of mixing characteristics on the catalytic activity.

3. Objectives

3.1 To investigate and propose the efficient system employing spinning disk reactor for sodium hydroxide catalyzed transesterification of waste cooking oil and methanol in order to dramatically enhance both of mass and heat transfer for reaction.

3.2 To explore the effects of operating parameters and design parameters on the catalytic activity and biodiesel production rate of the transesterification of waste cooking oils with methanol and to compare with those of the conventional mechanical stirred reactor.

4. Methodology

4.1 Materials

Waste cooking oil (WCO) is procured from a local restaurant in Bangkok, Thailand. The received WCO is filtered through normal sieve to remove food debris and heated to evaporate the possible water content. Methanol (99 %) (AR grade) and NaOH used in the experimental work are obtained from Sigma–Aldrich. he FAMEs standards, which include methyl palmitate, methyl stearate, methyl oleate, methyl linoleate, and methyl linolenate, are purchased from Merck.

4.2 Experimental setup

Fig. 1 is a simplified depiction of the spinning disk reactor (SDR). The SDR system consisted of two parallel coaxial discs: one stationary and the other rotational with controllable rotational speed. The main parts are a stainless-steel disk driven by a motor and a stationary cylindrical chamber. System temperature is controlled by recirculating water inside the disk and chamber. The SDR is 14 cm in diameter. The liquid distributors are two straight tubes in parallel and the radial distance of each distributor is 1 cm from the disk axis. Both tubes have a 3-mm hole at the end that is placed 5 mm from the disk. Moreover, one stationary can be movable for varying the gab between one stationary and the other rotational discs. The parameters effect on biodiesel yield will be tested following:

4.2.1 The effect of disk rotational speed (300-2400 rpm) on biodiesel yield will be tested at methanol/waste cooking oil mole ratio is 6 and using NaOH catalyst 1%wt. Therefore, the optimal disk rotational speed will be obtained.

4.2.2 The effect of methanol/waste cooking oil mole ratio (6, 9 and 12) on biodiesel yield will be tested at optimal disk rotational speed in 3.2.1.

4.2.3 The effect of gab between one stationary and the other rotational discs on biodiesel yield will be tested at optimal condition from 3.2.1 and 3.2.2.

4.2.4 Type of alcohol (ethanol and methanol) will be studied.

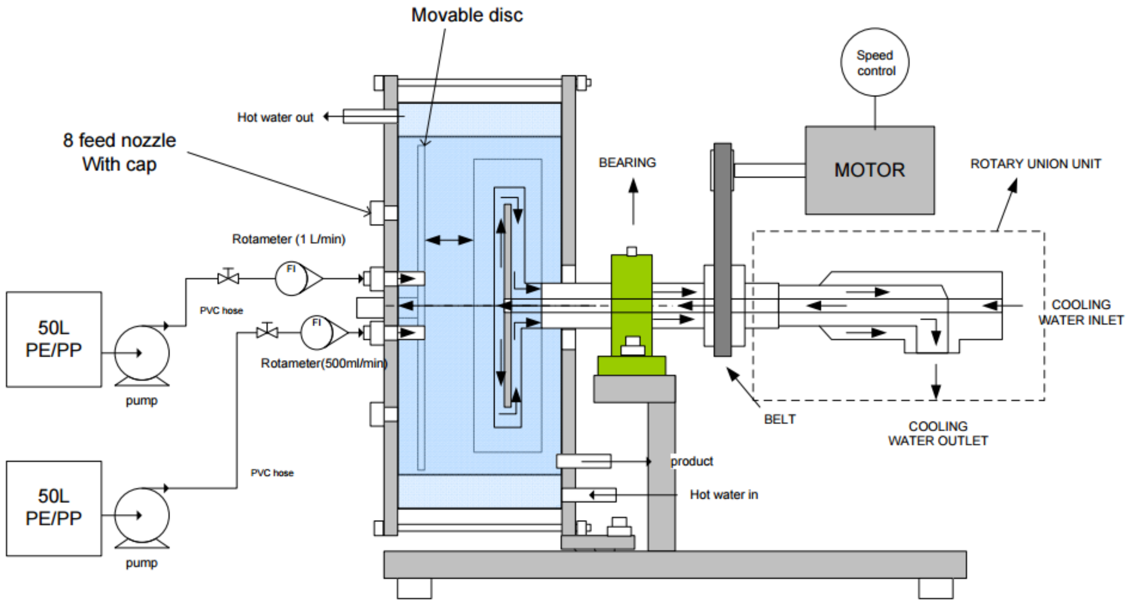

Fig. 1 Schematic diagram of experimental spinning disk apparatus to be used for NaOH catalyzed transesterification reaction.

4.3 Analytical method

The methyl esters yield was analyzed according to EN 14103 using a Perkin Elmer gas chromatography, equipped with a ZB5-HT capillary column (0.25 mm × 30 m). Helium was used as a carrier gas. The oven temperature ramp program was started from 150 °C and held for 5 min, 170 °C with a rate of 10 °C/min and held for 5 min, 220 °C with a rate of 3 °C/min. Temperatures of the injector and detector were 250 °C. Methyl ester yield was calculated by Eq. (1).

$$\% \, Yield = \frac{(\sum A) - A_{EI}}{A_{EI}} x \frac{C_{EI} x V_{EI}}{m} x 100\% \tag{1}$$

where $\sum$A is total peak area, AEI is the peak area that corresponds to methyl heptadecanoate, CEI is the concentration of the methyl heptadecanoate solution (mg/mL), VEI is the volume of methyl heptadecanoate (mL) and m is the mass of the biodiesel sample (mg). The biodiesel sample was washed with distilled water at a water: biodiesel ratio of 0.5:1 by volume for 3 times at ambient temperature using a stirrer speed of 200 rpm (Choedkiatsakul et al., 2013).

4.4 Kinetic study

The reaction was assumed to obey pseudo-first order kinetics as a function of the concentration of TG (Chuah et al., 2017; Sivakumar et al., 2013). Due to the excess methanol concentration, methanol was not considered as a limiting reactant. Excess methanol shifts the reaction forward to the desired product. The reaction kinetics is expressed in Eq. (2).

$$-r_{TG} = kC_{TG} \tag{2}$$

Where C_{TG} is the molar concentration of triglycerides in mol/L, r_{TG} is the rate of reaction of triglycerides with alcohol in mol/L.min, t is the reaction time in min and k is rate constant in min-1. From the literature, X. Feng et. al. studies the residence time distribution (RTD) in a spinning disc reactor, the results show that the reactors flow regime were seems to be closer to well mixed reactor (and perfect mixing) (Feng et al., 2013). Hence, an isothermal steady state CSTR design equation was used , the component mass balance equation is:

$$F_{TG0} - F_{TG} + V(-r_{TG}) = 0 \quad (3)$$

Where FTG0 is the initial molar flow rate of triglycerides in mol min-1, FTG is the molar flow rate of triglycerides in mol min-1 and V is the volume of reaction mixture. Since for a flow reactor F= QC and since Q (volumetric flow rate) is constant (assuming constant specific volume of liquid in the reaction system), then Eq. (3) becomes

$$QC_{TG0} - QC_{TG} + V(-r_{TG}) = 0 \quad (4)$$

Substitute for *r*, and using Eq. (2), the following equation can be obtained.

$$\frac{V}{Q} = \tau = \frac{X_{TG}}{k(1-X_{TG})} \quad (5)$$

Eq. (5) can then be used to determine the value of *k*. X_{TG} is the determined conversion of triglycerides and τ is the residence of each experimental run.

4.5 Calculation of yield efficiency

Yield efficiency or called energy efficiency as defined in Eq. (6) is proposed to quantify the efficiency of the biodiesel production system. It represents the amount of biodiesel produced per unit energy supplied to the production system. In this study, values of yield efficiency of different process intensification reactors are compared with the one obtained in this study using SDR in order to find the most suitable reactor for biodiesel production.

$$Yield\ efficiency = \frac{Amount\ of\ product\ produced\ (g)}{Power\ supplied\ (J\ s^{-1}) x\ Reaction\ time\ (s)} \quad (6)$$

5. Results and discussion

The preliminary result indicated that the spinning disc reactor (SDR) can produce high biodiesel yield in only 2-3 s of residence time and the reaction reached steady state after 10 min. The following sections reported the effects of important operating parameters on the yield of biodiesel using RPO and WCO as the feedstocks

5.1 Effect of type of alcohol on biodiesel yield

Due to the ethanol is produced from a number of crops such as potatoes, sugarcane, grains, corn and sorghum. Fatty acid ethyl esters (FAEEs) present a higher cetane number and calorific value, oxidation stability and lubricant characteristics than methyl esters, and also have lower tail pipe emissions. Therefore, the effect of type of alcohol was investigated. Biodiesel was produced from palm oil on ethanolysis using 1 wt.% NaOH at temperature at 60 °C and ethanol to oil molar ratio 6:1. High ethyl esters yield of 97% and 96.5% was obtained when using MS and SDR reactor, respectively. For Biodiesel production from palm oil on methanolysis using 1 wt.% NaOH at temperature at 60 °C and methanol to oil molar ratio 6:1. High ethyl esters yield of 96% and 96.7 was obtained when using MS and SDR reactor, respectively. However, the transesterification reaction is reversible in nature, so excess amount of alcohol is required to keep the reaction in the forward direction. In addition, methanol is cheaper than ethanol., methanol was choose to be the raw feed stock in next section.

5.2 Effect of operating temperature

The transesterification was performed at different temperatures over the range of 40 to 60 °C to determine a suitable operating temperature for the biodiesel production operated at a methanol to oil molar ratio of 6 and catalyst loading of 1 wt% NaOH. Table 1 summarizes the FAME yields achieved at different temperatures for RPO and WCO feedstocks. The results shows that increasing temperature from 40 to 60 °C resulted in increasing FAME yield from 78.2 to 97.0% for RPO and 74.1 to 90.9% for WCO. The operating temperature of 60 ^{o}C was used in the following experiments.

Table 1 Effects of operating temperature and type of oil feedstock on FAME yield in SDR (methanol to oil molar ratio = 6, feed flow rate = 260 mL min^{-1}, rotational speed = 1,500 rpm and NaOH = 1.0% wt oil).

Temperature °C	RPO			WCO		
	40	50	60	40	50	60
FAME yield (%)	78.2	83.1	92.9	74.1	78	87.6
Rate constant for transesterification (min^{-1})	115.7	154.7	439.7	89.5	129.2	244.4

From the experimental results, the values of the reaction rate constant (k) based on first order reaction kinetics can be determined by plotting the relationship in Eq. (5) as shown in Figure 2 (a) and (b). From Table 1, the reaction rate constant (k) was increased from 115.71 to 439.72 and 89.46 to 244.39 min^{-1} for RPO and WCO, respectively, when increasing the temperature from 40 to 60 °C. It should be noted that the regression coefficients were in the range of 0.95-0.99. The reaction rate constant obtained in SDR was found to be about 20,000 fold higher than that of MS (only 0.031 min^{-1}) as reported by Chuah et.al. (Chuah et al., 2017). Activation energy (*E*a) and frequency factor (*A*) were calculated according to the Arrhenius equation, Eq. (7).

$$k = Ae^{\frac{-E_A}{RT}} \quad (7)$$

Since the activation energy is dependent on temperature, the rate constants with respect to any temperatures (within the validity of the Arrhenius equation) can be computed using Eq. (8).

$$\ln(k) = \left[\frac{-E_a}{RT}\right] + \ln(A) \quad (8)$$

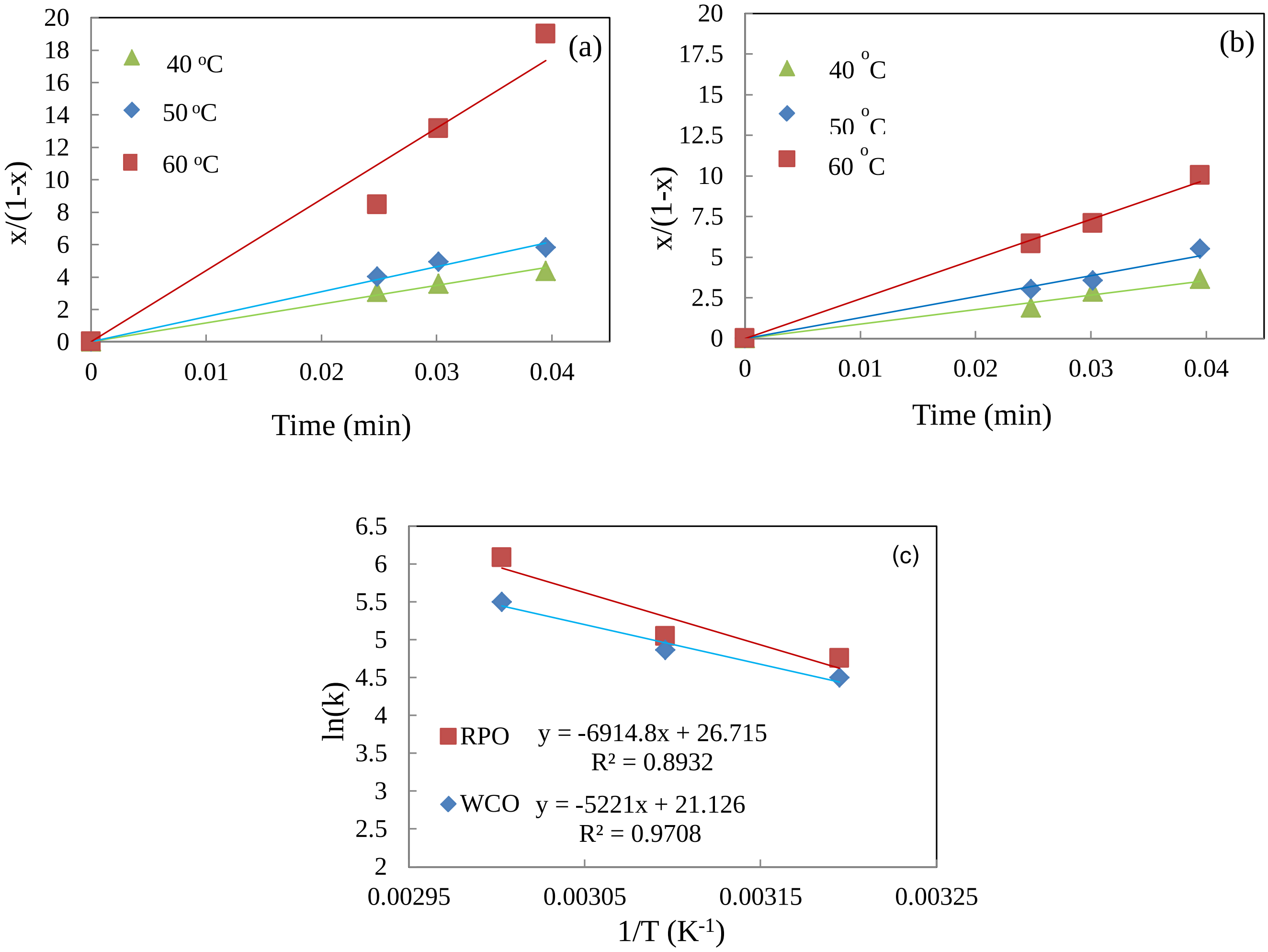

Fig. 2 Kinetic studies of NaOH catalyzed transesterification of (a) RPO and (b) WCO in SDR and (c) Arrhenius plot in the temperature range of 40-60 °C.

By plotting the relationship between ln k and 1/T in Figure 2 (c), the obtained values of the activation energy for SDR were 57.5 and 43.4 kJ/mol for RPO and WCO, respectively. They are much lower than those reported for the transesterification of WCO when using other reactors; for examples, 89.7 kJ/mol with hydrodynamic cavitation (HC) (Chuah et al., 2017), 58.9 kJ/mol with ultrasonic (US) (Bargole et al., 2017) and 92.7 kJ/mol with mechanical stirring (MS) (Chuah et al., 2017). The activation energy for the transesterification of WCO were lower than RPO, in turn less energy required to activate the chemical reaction. It is likely that cooking process causes the refined palm oil, triglyceride, to break-down to diglycerides, monoglycerides, and free fatty acids (FFAs) (Haigh et al., 2014) and thus less activation energy is required for converting WCO to biodiesel compared to the use of RPO feedstock.

5.3 Effect of methanol to oil molar ratio

The methanol to oil molar ratio is one of most important variable affecting the oil conversion, yield of biodiesel and biodiesel production cost. To study its effect, the methanol to oil molar ratio was varied from 3 to 12. The reaction was operated using 1 wt% NaOH catalyst loading at 60 °C and a rotational speed of 1,500 rpm. The obtained results (Figure 3) show that for both types of oil, the optimum methanol to oil molar ratio was at the same value of 6. The maximum yields of biodiesel of 92.9 and 87.6% were obtained when using RPO and WCO, respectively. The stoichiometry of biodiesel forming reaction via transesterification is 3 mol of biodiesel and 1 mol of glycerol produced from 1 mol of TG and 3 mol of methanol. However, this reaction is reversible and, therefore a higher molar ratio is required to shift the reaction equilibrium as well as to enhance the contact between the immiscible methanol and triglyceride reactants (Musa, 2016). However, a high amount of methanol also lowered the concentration of TG and thus decreased the FAME yield. In addition, excessive use of methanol in the transesterification reaction also increased the costs of the reactant and the subsequent methanol recovery. Therefore, the methanol to oil molar ratio of 6 was used in the subsequent experiments.

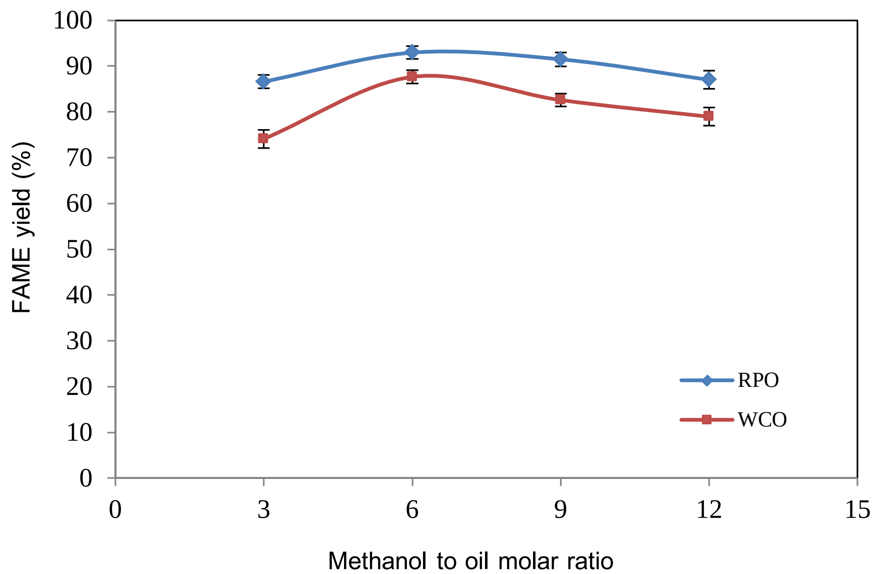

Fig. 3 Effect of methanol to oil molar ratio on FAME yield using SDR for RPO and WCO (NaOH = 1.0% wt oil, feed flow rate = 260 mL/min and rotational speed = 1,500 rpm).

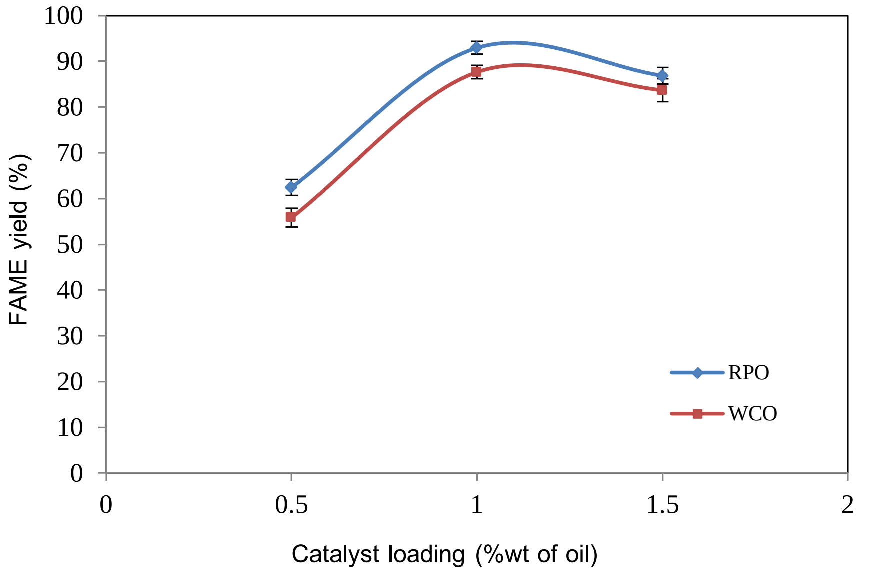

Fig. 4 Effect of catalyst loading on FAME yield using SDR for RPO and WCO (methanol to oil molar ratio = 6, feed flow rate = 260 mL/min and rotational speed = 1,500 rpm).

5.4 Effect of catalyst loading

Removal of a catalyst from a reaction mixture can cause a major problem but its amount also affects the rate of reaction. Thus, a suitable catalyst loading should be determined. The effect of catalyst loading on FAME yield is shown in Figure 4. The amount of NaOH was varied; 0.5, 1.0and 1.5 wt% under the condition of methanol to oil molar ratio of 6, temperature of 60 °C, feed flow rate of 260 mL min-1 and rotational speed of 1,500 rpm. It was found that the FAME yield was increased with increasing catalyst loading and the maximum yields were 92.9% for RPO and 87.6% for WCO at the same optimum catalyst loading of 1 wt%. When using NaOH as catalyst, methoxide ions were created by dissolving sodium hydroxide in methanol. The methoxide ions are needed for the biodiesel production reaction. Unfortunately, the reaction also creates a molecule of water which causes formation of soap through a chemical reaction called saponification. It should be noted that too high catalyst loading could cause side reactions such as saponification and difficult separation of esters from glycerol and water (Lin et al., 2014). Therefore, the subsequent experiments for biodiesel production were based on the condition of a methanol to oil molar ratio of 6 and a catalyst loading of 1 wt% of oil.

5.5 Effect of rotational speed

Figure 5 illustrates the obtained biodiesel yields at various values of rotational speed when all other operating parameters such as alcohol to oil molar ratio, catalyst concentration and total flowrate were kept constant. It can be clearly seen that an increase in rotational speed from 500 to 1000 rpm resulted in an increase in the FAME yield from 92.9 to 97.0% for RPO and 87.6 to 90.9% for WCO. The yield enhancement could be described by the improved mass transfer and micro-mixing efficiency by centrifugal force in an SDR (Chen and Chen, 2014). A thin liquid film was generated on the disk surface and the intensive mixing increased the contact between the two immiscible reactants, reducing mass transfer resistance, and enhancing overall reaction rate during the transesterification. As a result, a high biodiesel yield can be achieved in an SDR with a very short residence time. However, the FAME yield was found to decrease by further increasing the rotational speed over 1,500 rpm. This could be due to the shorter residence time of the reactants in the SDR. The approximate analytical expression for residence time of reactants on the disc was developed by Munjal et al. (Chen and Chen, 2014; Munjal et al., 1989):

$$\tau = \frac{3}{4}\left(\frac{12\pi^2\mu}{\rho Q^2\omega^2}\right)^{1/3}\left(r_0^{4/3} - r_i^{4/3}\right) \quad (9)$$

Where τ is residence time (s), μ is viscosity of liquid (Pa.s), Q is reactant flow rate (m^3/s), r_o is radius of the disc (m) and r_i is radial position of the liquid distributor (m), and ω is rotational speed (rad/s).

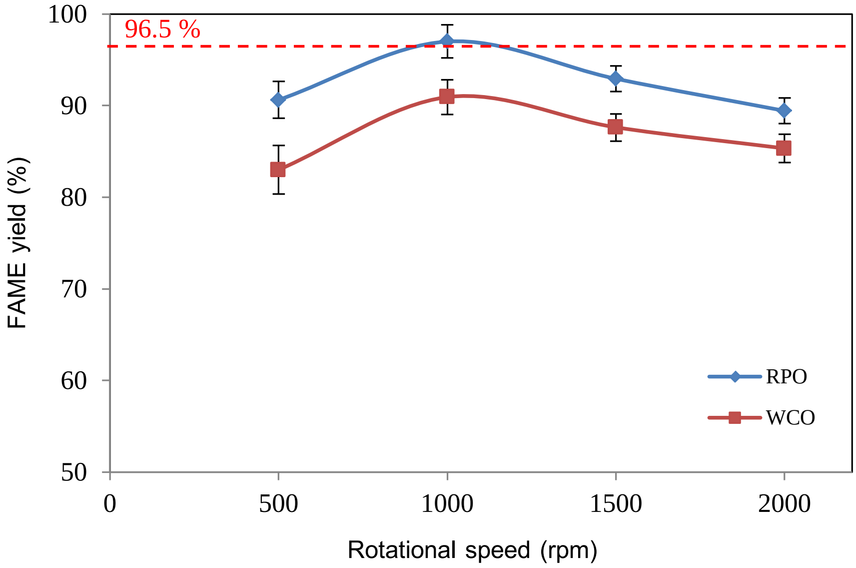

Fig. 5 Effect of rotational speed on FAME yield using SDR for RPO and WCO (methanol to oil molar ratio = 6, feed flow rate = 260 mL/min and NaOH = 1.0 wt% oil).

For example, at a total flow rate of RPO and methanol of 260 mL/min when increasing the rotating speed from 1,500 to 2,000 rpm, the liquid residence time was decreased from 1.81 to 1.49 s. This might be attributed to the decreased FAME yield as presented in Figure 4. It should be noted that the constraint of FAME yield of 96.50% following ASTM standard was achieved when using the RPO as reactant. The use of WCO as a feedstock to produce biodiesel in the SDR could not meet this standard with the range of operating parameters studied but it still provided relative high FAME yield (about 90%). The results demonstrate that this SDR can achieve a high FAME yield within a very short residence time compared to other reactors. In addition, it indicated that reactor volume required for continuous biodiesel production can be reduced.

5.6 Effect of gab between one stationary and the other rotational discs on biodiesel yield

Table 2 show the effect of the gap size between the disks on the FAME yield in SDR at 60°C – disc speed 1,000 rpm, total flow rate 260 mL/min. These show that FAME yield is increased from about 91 to 94 % when the gap size decreases from 0.40 mm to 0.0.2 mm at rotational speed is 1000 rpm. This could be explained by higher mixing intensity brought about at the smaller gap size. It could reasonably argued that shear stress is increased as the separation distance between two disks is decreased thus resulting in more intensive mixing. On the other hand operation at a smaller gap size may reduce the effective mean residence time of the reactor which would lead to a reduction in FAME yield. The simulations can be described later would support this argument. Therefore, the rotational speed influences fluid flow and residence time distribution inside the inter-disc space should be determined by simulation of the hydrodynamics in the future.

Table 2 Effect of the gap sizes on the FAME yield at 60°C: disc speed 1,000 rpm, total flow rate 260 mL/min.

Gap sizes (mm)	FAME yield (%)
0.2	94.2
0.3	91.3
0.4	91.0
Single disc	90.9

5.7 Performance comparison of different mixing types on FAME yield

The previous sections revealed the promising results of the use of SDR for transesterification of refined palm oil to produce biodiesel. It should be interesting to compare the reaction performance with other reactors with different mixing types. Table 2 summarizes the data of the reaction time and FAME yield reported in literatures. The values were based on the same operating condition of a methanol to oil molar ratio of 6:1, 1 wt% NaOH and 60 °C operating temperature (Chuah et al.;2013). Gole et al. and Chuah et al. reported that ultrasonic cavitation (US) and Hydrodynamic cavitation (HC) achieved 93% and 98% FAME yield after 40 and 15 min of the reaction time at their optimized conditions, respectively (Gole et.al., 2013; Chuah et al., 2015). In comparison with the results of the SDR reactor in this study, the FAME yield as high as 97.0% could be achieved with a very short residence time of 2–3 seconds at a molar ratio of 6, NaOH concentration of 1.0 wt%, temperature of 60 °C, flow rate of 260 $mL.min^{-1}$, and rotational speed of 1,000 rpm. It obviously offers a significant reduction in the reaction time for the transesterification especially when compared with the reaction time of 90 minutes required for the conventional mechanical stirrer. Moreover, the performance of the SDR in term of yield efficiency is presented in Table 2. Yield efficiency is defined as the amount of product per unit energy required for the reaction. It was found that the highest yield efficiency and shorter reaction time were achieved by using SDR compared to MS, HC and US. It was about 8.5 times more efficient in terms of energy consumption compared to MS. The overall biodiesel production costs are dependent on the feedstocks cost and also consumption of total energy. The results demonstrate that this SDR can achieve a high biodiesel yield with a very short residence time, high yield efficiency, indicating that the reactor volume required for continuous biodiesel production can be reduced. Moreover, the SDR has a very simple structure with easy operation and maintenance. Therefore, SDR is a promising process intensification reactor for economical continuous biodiesel production in the industrial scale.

Table 3 Comparative performance of SDR with hydrodynamic cavitation, ultrasonic cavitation and mechanical stirring reactor.

Reactor	Oil	Catalyst	Reaction time (min)	FAME yield (%)	Yield efficiency (g J^{-1})x10^{-4}	Reference
Spinning disc (SDR)	Refined palm oil	NaOH	<3s	97.0	13.7	This study
	Waste cooking oil	NaOH	<3 s	90.9	12.9	This study
Mechanical stirred (MS)	Refined palm oil	NaOH	90	97.7	1.6	This study
Mechanical stirred (MS)	Refined cooking oil	KOH	90	97.0	1.5	Gole et.al., 2013
Hydrodynamic cavitation (HC)	Refined cooking oil	KOH	15	98.0	12.8	Chuah et al., 2015
Ultrasonic (US)	Nagchampa oil	KOH	40	93.0	0.1	Gole et.al., 2013

* The data reported by using methanol-to-oil molar ratio = 6, catalyst loading = 1%wt of oil, reaction temperature = 60 °C.

6. Conclusions

Continuous biodiesel production from refined palm oil (RPO) and waste cooking oil (WCO) by using a spinning disc reactor (SDR) was investigated and compared to a mechanically stirred reactor. Using SDR was proved to be effective in terms of higher yield efficiency and achieved high fatty acid methyl ester content 97.0 % satisfied the minimum requirement of ASTM 14103 in a shorter reaction time when using RPO as the feedstock. The transesterification was conducted under optimized conditions, i.e. methanol to oil molar ratio of 6:1, NaOH concentration of 1.0 wt%, reaction temperature of 60 °C, total flow rate of 260 mL/min and rotational speed of 1,000 rpm, providing a FAME yield of 97.0% and a yield efficiency of 13.7×10^{-4} and 12.9×10^{-4} g/J corresponding to residence time of 2–3 s for RPO and WCO, respectively. Lower activation energy was also obtained as 57.5 and 43.4 kJ/mol for RPO and WCO, respectively compared to the conventional mechanical stirrer. This obviously offers a significant reduction in the reaction time for the transesterification especially when compared with other reactors, proving that SDR is a promising intensification reactor for continuous biodiesel production. Furthermore, an SDR has the additional advantages of a simple structure and maintenance.

7. Future scope of study

In the present study, biodiesel was produced from refined palm oil and waste cooking oil with help of methanol and ethanol to understand the effect of alcohol on biodiesel yield and reaction parameters were optimised using spinning disc reactor (SDR) . To have further improvement in biodiesel yield, scope lies in use of heterogeneous catalysts in SDR. In addition, the resulting data is being compiled in a journal, where we relate our finding that mass transfer is key for a good result. However, significant knowledge for explaining the performance of SDR is lacking; therefore, the mass transfer in the spinning disc should be studied deeply. The information obtained from this study is expected to provide basic knowledge on the optimal design of the SDR, aiming at providing useful information for the scaling up of the SDR for chemical reactions and/or other operations.

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LIST OF PUBLICATIONS

1. **International conferences**

   Intensification of biodiesel synthesis from refined palm oil in a spinning disc reactor: Pure and Applied Chemistry International Conference 2017 (PACCON 2017) February 2-3, 2017 Centra Government Complex Hotel & Convention Centre

2. **International publications**

   Intensification of continuous biodiesel production using a spinning disc reactor : Journal of Chemical engineering of japan : **Under review**