Performance test of a 6-stage continuous reactor for palm methyl ester production

T. Leevijit a,b,*, C. Tongurai c, G. Prateepchaikul b, W. Wisutmethangoon b

a The Joint Graduate School of Energy and Environment, King Mongkut’s University of Technology, Thonburi, Bangkok 10140, Thailand
b Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand
c Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand

Received 28 September 2006; received in revised form 28 November 2006; accepted 28 November 2006
Available online 26 January 2007

Abstract

Effects of residence time (3–12 min), stirrer speed (0–800 rpm), and NaOH concentration (0.25–1.0 wt% of oil) on the production performance of the designed 6-stage continuous reactor (2.272 l) for transesterification of palm oil were investigated at molar ratio of methanol to oil of 6:1 and temperature of 60 °C. Higher stirrer speed increased the reaction rate up to an appropriate speed but excessive stirrer speed decreased the reaction rate. Inappropriate stirrer speed runs dramatically decreased the production capacity of the reactor. Higher NaOH concentration significantly increased reaction rate and production capacity of the reactor. The reactor had a residence time distribution equivalent to 5.98 ideal CSTRs in series and a production performance equivalent to a plug flow reactor. At NaOH of 1.0 wt% of oil, the reactor could produce saleable biodiesel within residence time of 6 min in which a production capacity was 17.3 l/h and a power consumption of stirrer was 0.6 kW/m 3.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Continuous reactor; Transesterification; Methyl esters; Biodiesel; Palm oil

1. Introduction

Biodiesel (fatty acid esters) has a great potential as an alternative diesel fuel. Its fuel properties are quite similar to those of conventional diesel fuels (Ali et al., 1995; Rao and Gopalakrishan, 1991; Feuge and Gros, 1949; Dunn and Bagby, 1995; Chang et al., 1996; Kalam and Masjuki, 2002; Schwab et al., 1987; Antolin et al., 2002; Lang et al., 2001). It can be produced from renewable resources such as vegetable oils and tallow. It also provides environmental benefits especially carbon dioxide saving that prevents the greenhouse effect (Peterson and Hustrulid, 1998). Thus, it has become more attractive in many countries, including Thailand (an agricultural-based and diesel-imported country). In Thailand, several economic oilseeds can be used as a raw material but oil from palm fruits is the highest potential source (Thai Parliament, 2002). The government has planned to produce biodiesel of 8.5 Ml/d in 2012. Success of biodiesel commercialization is an important factor for Thailand’s sustainable development from which the positive economic effects and an increase of energy security would be achieved. Consequently, production technologies are urgently required and being developed in Thailand.

In past several years, batchwise transesterifications of various vegetable oils were intensively investigated (Antolin et al., 2002; Boocock et al., 1996, 1998; Alcantara et al., 2000; Muniyappa et al., 1996; Mohamad et al., 2002; Freedman et al., 1984, 1986; Noureddini and Zhu, 1997; Vicente et al., 1998; Darnoko and Cheryan, 2000a; Leevijit et al., 2004) to study the effect of various variables, to find the kinetics, and to optimize the production

* Corresponding author. Address: Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand. Tel.: +66 74 287035; fax: +66 74 212803.
E-mail address: leetheerayut@yahoo.com (T. Leevijit).
condition. Published papers have been reviewed in at least four papers (Ma and Hanna, 1999; Srivastava and Prasad, 2000; Schuchardt et al., 1998; Fukuda et al., 2001). Important variables affecting the reaction rate and conversion are catalyst type and concentration, reaction temperature, molar ratio of alcohol to oil, mixing intensity, and purity of reactants. For oil containing free fatty acid ≤1%, alkali-catalyzed transesterification is suitable and the typical reaction conditions are as following: molar ratio of alcohol to oil is 6:1; reaction temperature is near the boiling point of alcohol (60–70 °C for atmospheric pressure system); and often used catalysts are NaOH and KOH at concentrations ≤1.0 wt% of oil.

The common method for a small scale biodiesel production is a batch transesterification process but a continuous process can generally provide lower production cost and more uniform product quality for a large scale production (Ma and Hanna, 1999; Srivastava and Prasad, 2000; Noureddini et al., 1998; Darnoko and Cheryan, 2000b). A few continuous reactors for biodiesel production have been developed and evaluated their performances. Darnoko and Cheryan (2000b) evaluated a continuous stirred tank reactor (CSTR) for transesterification of refined palm oil. Noureddini et al. (1998) examined a continuous process consisting of two motionless mixers, a high-shear mixer, and a residence tube for transesterification of soybean oil. Harvey and Mackley (2002) assessed an oscillatory flow reactor for transesterification of rapeseed oil. According to the European Union standards for alternative diesel fuels, the minimum acceptable purity of fatty esters as saleable biodiesel is 96.5 wt% (Karaosmanoglu et al., 1996). Both simple and complex continuous reactors could produce saleable biodiesel in which the required residence time depended on reaction conditions and a residence time distribution (RTD) of the reactor.

However, there was no literature reporting performances of a simple continuous reactor in a form of multi-stage mechanically stirred tank for transesterification of vegetable oils. Leevijit et al. (2006) have designed a 6-stage continuous reactor for alkali-transesterification of refined, bleached, and deodorized (RBD) palm oil with methanol to produce methyl esters (ME). The reactor was designed as consisting of 6 units of CSTR in a series arranged in vertically stacked type. Each unit was separated from each other by separating plates with a small opening. Rushton turbine was located at the middle height of each unit. All turbines were fixed on only one shaft driven by a stirrer motor at the top-end of the shaft. Four standard wall-baffles were also preferred for promoting the better mixing. Important dimensions of each unit of the reactor are as followings: tank diameter = 81.0 mm, tank height = 81.0 mm, impeller diameter = 48.0 mm, blade width = 10.0 mm, blade length = 12.0 mm, baffle width = 7.0 mm, and the opening area of a separating plate (excluding the shaft area) = 4% of cross-area. Its effective volume was measured to be 2.272 l. The objectives of this paper were to evaluate effects of residence time, stirrer speed, and NaOH concentration on the production performance of the reactor and to characterize necessary parameters for scaling-up including production yield (final product/fed oil), production capacity of the reactor, RTD of the reactor, and power consumption of a stirrer.

2. Methods

2.1. Materials

Commercial grades of RBD palm oil, methanol (purity of 95%), and NaOH (purity of 98%) were used. A free acid content of oil determined according to AOCS official method Ca 5a-40 (Link, 1989) was 0.02 wt% of oil. Initial compositions of oil analyzed by thin layer chromatography/flame ionization detector (TLC/FID) were triglyceride (TG) of 95.7 wt%, diglyceride (DG) of 3.7 wt%, and monoglyceride (MG) of 0.6 wt%. Pro-analysis grades of hexane, diethyl ether, formic acid, and benzene were used in TLC/FID analysis.

2.2. Experimental set-up

The experimental set-up for continuous transesterification is shown in Fig. 1. Storage tanks of 351 and 10 l were used to store oil and methanol/NaOH solution, respectively. Peristaltic pumps (Watson Marlow: model 323 E/D and model 401U/D) that could run at various constant speeds were used to pump reactants to the insulated reactor. In-line flow meters (500 ml glass tube calibrated and marked at every 50 ml) were used to measure reactant flow rates. Time spent for emptying the known volume of reactant in the glass tube was measured by a clock (reading resolution = 0.01 s and measured time >18 s). Then, the

![Fig. 1. Schematic diagram for continuous transesterification of RBD palm oil](image-url)
flow rate could be calculated. Flow rates of reactants were calibrated and monitored for all experiments. Experiments could be run in the range of ±2.5% of desired flow rates. A 1 kW heater, a stirrer, and a temperature control unit were also installed in oil tank to preheat the oil. A 3.5 kW in-line heater was installed in each line of reactant. Temperature probes connected with temperature control units were installed at inlet ports of the reactor to measure and to control inlet temperatures of reactants. Heating systems could control inlet reactant temperatures to within ±1.0 °C of the set point. An available motor (200 W and 1,000 rpm) was used to drive a stirrer. Its rotational speed was controlled by a variac (0–260 V). The system could work in the range of ±5 rpm of the set speed. The product could be discharged from the reactor via an overflow discharge port at the top of reactor and samples of product were collected through the sampling port. The product was then stored in a product storage tank (35 l). Moreover, the product had to be further processed in downstream processes consisting of glycerol (GL) separation, water washing, and water removing to obtain the final product of biodiesel.

2.3. Experimental procedure

Initially, the empty reactor was preheated. Both feed pumps were turned on to circulate reactants from storage tanks through in-line flow meters, in-line heaters, and return to storage tanks. During this, pump flow rates were preset. Next, all heaters were turned on and pre-start operation was run until inlet temperatures of reactants were constant. After that, reactants were fed into the reactor. When the whole reactor was filled, the stirrer motor was turned on and the speed was set. Pump flow rates were then finely adjusted. When the desired operation condition was achieved, timing was started. During the experiment, reactant flow rates, reactant inlet temperatures, product temperature, and stirrer speed were monitored. A sample of about 5 ml of the product was collected at three normalized residence time (time/residence time) for all experiments. The sample was immediately washed with a large amount of water to stop the reaction and to purify the sample. The ester phase was then centrifuged and kept for further analysis. In addition, for each experimental condition, the experiment was run at least twice and the average result was reported here in which separate test revealed that the narrow deviation of the result was obtained.

Based on the effective volume of the reactor, the desired total flow rates of oil and solution were 757.3, 378.7, 252.4, and 189.3 ml/min for residence times (volume of reactor/total flow rate of reactants) of 3, 6, 9, and 12 min, respectively. The flow rate ratio of oil to solution was held constant at 3.81:1 for all experiments to obtain the calculated molar ratio of methanol to oil of 6:1. This flow rate ratio was calculated based on the available density of RBD palm oil at 15.6 °C (0.9180 kg/l) (Srivastava and Prasad, 2000) and the density of methanol at 20 °C (0.792 kg/l) (Perry et al., 1997). Although, densities of reactants changed with temperature, our separate tests revealed that the density of RBD palm oil changed only 2.84% over 45 °C of temperature change and the result was in the same range for methanol. Hereby, the effect of temperature change was neglected for experimental set-up. The molecular weight of RBD palm oil was calculated based on known fatty acids of palm oil (Kincs, 1985). Molecular weights of TG, DG, and MG were 849.5, 597.0, and 344.5 kg/kmol, respectively, and a molecular weight of methanol was 32.04 kg/kmol (Perry et al., 1997).

The solution of NaOH in methanol was freshly prepared for each experiment; for example, at NaOH concentration of 1.0% wt of oil (35 g/l of solution), the weighed NaOH of 35.00 ± 0.05 g was dissolved in methanol of 1000 ± 5 ml. Sodium hydroxide was weighed by a balance (reading resolution = 0.01 g) and the volume of methanol was measured by a measuring tube (expectable resolution = 2.5 ml).

2.4. Sample analysis

The sample of product was analyzed by TLC/FID using an Itromscan MK-6s with Chromarods type S-III quartz rod (Mitsubishi Kagaku Iatron). The sample was diluted in hexane and 1 µl of the solution was spotted on the rod. Rods were developed in hexane/diethyl ether/formic acid (50:20:0.3 vol/vol/vol) for 8 cm and in hexane/benzene (1:1 vol/vol) for 10 cm. Rods were dried and scanned under the following conditions: hydrogen flow rate of 160.0 ml/min, air flow rate of 2.0 l/min, and speed of 30 s/scan. TG, DG, MG, and ME were effectively separated. Peak areas were calculated with a chromatography data system ChromStar and represented as weight percentages (wt%) on a GL-free basis. The analysis was repeated three times for each sample.

3. Results and discussion

3.1. Production performance of the 6-stage continuous reactor

3.1.1. Effect of stirrer speed

Transesterification of vegetable oils with alcohol consists of a number of consecutive and reversible reactions (Schwab et al., 1987; Freedman et al., 1986). TG is converted stepwise to DG, MG and finally GL as shown in Eq. (1). One mole of ester is liberated at each step.

\[
\begin{align*}
TG + A & \rightleftharpoons DG + E \\
DG + A & \rightleftharpoons MG + E \\
MG + A & \rightleftharpoons GL + E
\end{align*}
\]

where A and E are alcohol and ester, respectively.

In this work, an amount of produced ME represented by a purity of ME in product as shown in Eq. (2) was used as a process result indicating the overall conversion of reaction
and the production rate of ME was used as the overall reaction rate.

Purity of ME (wt%)

\[ = \frac{W_{ME}}{W_{ME} + W_{TG} + W_{DG} + W_{MG}} \] 

(2)

where \( W_{ME} \), \( W_{TG} \), \( W_{DG} \), and \( W_{MG} \) are weight percentages of ME, TG, DG, and MG in final product on a GL-free basis (wt%), respectively.

An effect of stirrer speed on the overall reaction rate was investigated at NaOH of 1.0 wt% of oil. Experiments were run at residence times of 3, 6, 9, and 12 min. For each residence time, the stirrer speed was varied in the range of 0–800 rpm. But, for residence time of 3 min, the experiment was omitted at stirrer speed of 100 rpm due to the unstable of motor speed. In case of the stirrer motor was turned off (0 rpm), the lower limit of mixing caused by fluid flow alone was examined.

Produced purities of ME were less than 20 wt% for all residence times when the stirrer motor was turned off and dramatically increased to exceed than 90 wt% when the stirrer motor was turned on. These results revealed that mixing significantly affected the reaction rate in which insufficient mixing could lead to a very slow reaction rate.

Fig. 2 clearly shows the effect of stirrer speed on the produced purity of ME when the stirrer motor was turned on. A same pattern was observed for all residence times. Increase of stirrer speed provided a higher purity of ME up to an appropriate speed. Further increase of stirrer speed did not provide a better result but a small decrease of purity of ME was observed. Noureddini et al. (1998) also observed this pattern in their experiments; however, the reason was still unclear.

In Fig. 2, produced purities of ME were in ranges of 93.8–95.8, 95.1–97.5, 97.0–98.2, and 97.3–99.2 wt% for residence times of 3, 6, 9, and 12 min, respectively. Appropriate stirrer speeds providing the highest purities of ME were 500 and 300 rpm for residence times of 3 and 6 min, respectively, and they were similar at 200 rpm for residence times of 9 and 12 min. Although produced purities of ME in the studied range were in narrow ranges, these small differences significantly affected the production capacity of the reactor. For example, for residence time of 6 min, if the reactor is run at the appropriate stirrer speed of 300 rpm, ME at the purity of 97.5 wt% is produced. But, if the reactor is run at an inappropriate stirrer speed of such 800 rpm, ME at less purity of 96.2 wt% is obtained. To produce ME at the purity of about 97.5 wt% by running the reactor at the stirrer speed of 800 rpm, the reactor has to be run at longer residence times of 9 or 12 min. As a consequent, the production capacity of the reactor significantly decreases to be about 67% and 50% of the appropriate stirrer speed run, respectively.

Furthermore, Fig. 3a–c also clearly show the effect of stirrer speed on weight percentages of remaining reactants (TG, DG, and MG) in product. The lowest weight percentages of remaining reactants were also found at the same appropriate stirrer speeds for all residence times as obtained in Fig. 2.

3.1.2. Effect of NaOH concentration

The effect of NaOH concentration on the produced purity of ME was investigated at concentrations of 0.25, 0.5, 0.75, and 1.0 wt% of oil. For each concentration, the reactor was run at residence times of 3, 6, 9, and 12 min and a stirrer was set at obtained appropriate speeds. The experiment was run twice for each condition and average results are shown in Fig. 4. Shaded bars represent purities of ME >96.5 wt%. At the same residence time, the higher purity of ME was obtained when the higher NaOH concentration was used. In the studied range, only NaOH of 0.75 and 1.0 wt% of oil could produce saleable biodiesel. However, to produce ME at the purity of about 97.5 wt%, NaOH of 1.0 wt% of oil required the residence time by approximately half of NaOH of 0.75 wt% of oil.

3.1.3. Comparison between the 6-stage continuous reactor and a well-mixed batch reactor

The highest weight percentages of produced ME and the lowest weight percentages of remaining TG, DG, and MG in product at various residence times were plotted and compared with our previous result for transesterification of RBD palm oil in a well-mixed batch reactor at the same reaction condition (Leevijit et al., 2004). The same weight percentages of produced ME and remaining TG, DG, and MG in product were found at the same reaction time in both reactors (the plots are not shown here). This finding revealed that, in the studied range, the 6-stage continuous reactor had the production performance equivalent to a plug flow reactor. The reactor could produce ME at
purities of 95.8, 97.5, 98.2, and 99.2 wt% within residence times of 3, 6, 9, and 12 min, respectively.

3.2. Characterizations of parameters for scaling-up

3.2.1. Production yield

Production yield is necessary information for calculating the production capacity of the laboratory scale reactor and for expecting the production capacity of the scaled-up reactor. This information is also necessary for economics analysis. Production yield (neglecting losses due to glycerol separation and washing processes) was determined at three selected production conditions (NaOH of 0.75 wt% of oil and residence time of 12 min, NaOH of 1.0 wt% of oil and residence time of 6 min, and NaOH of 1.0 wt% of oil and residence time of 12 min). The experimental setup in Fig. 1 was used in this experiment. The product of the reaction mixture of about 450 ml was collected and collecting time was recorded by a clock (reading resolution = 0.01 s and recorded time >90 s). The product was suddenly washed by hot water (≈100 °C) and further washed by water until it was clean in which GL, methanol, NaOH, and other impurities were completely removed. The product was heated at 120 °C for 30 min to remove water, cooled down to room temperature, and its volume was measured by a 500 ml measuring tube (expectable resolution = 2.5 ml). For each experiment, the flow rate of the fed oil was measured and, then, volumetric production yield could be calculated. The experiment was repeated three times for each condition and results are shown in Table 1.

Production yields were in the range of 94.0–97.3% and depended on the produced purity of ME. The greater amount of final product was obtained at the lower pro-

![Graphs](image-url)
produced purity of ME. At the same residence time, the higher NaOH concentration caused a small decrease of the production yield. Similarly, at the same NaOH concentration, the longer residence time also resulted in a small decrease of the production yield.

### 3.2.2. Production capacity of the 6-stage continuous reactor

Production capacities of the reactor at NaOH of 1.0 wt% of oil were calculated for residence times of 6, 9, and 12 min in which produced purities of ME were 97.5, 98.2, and 99.2 wt%, respectively. Volumetric production yields were experimentally obtained for purities of 97.5 and 99.2 wt% and it was interpolated for the purity of 98.2 wt%. Production capacities of the reactor were 17.3, 11.4, and 8.5 l/h for producing ME at purities of 97.5, 98.2, and 99.2 wt%, respectively.

### 3.2.3. RTD of the 6-stage continuous reactor

A RTD of the reactor was measured to characterize a state of mixing in the reactor. The measurement was performed at the selected residence time of 6 min (the shortest residence time that could produce saleable biodiesel). The stirrer was run at the appropriate speed of 300 rpm. The negative step change method (Paul et al., 2004) was used. A schematic diagram of the experiment was similar as shown in Fig. 1. But, the solution was replaced by ME and the heater in this line was turned off. The heated palm oil (60 °C) was used as a main fluid and a small amount of ME was used as a tracer. The flow rate of oil was set to obtain the desired residence time. Initially, oil and ME were fed into the reactor for an extended period of time to obtain a constant tracer concentration in an outlet stream (C<sub>out</sub> = C<sub>in</sub> = C<sub>b</sub> for time < 0). At time t = 0, the tracer supply was stopped so that C<sub>in</sub> = 0 for time t ≥ 0. Samples of the outlet stream were collected at pre-specified time intervals and analyzed by TLC/FID to determine the weight concentration of the tracer (C<sub>t</sub>). A washout function W(t), normalized tracer concentration, is defined as shown in Eq. (3). A dimensionless variance (σ<sup>2</sup>) and a number of ideal CSTR in a series (n) were calculated by Eqs. (4) and (5), respectively. The experiment was run twice and the average calculated n was 5.98 which very close to the number of stage.

\[
W(t) = \frac{C_t}{C_0}
\]

\[
\sigma^2 = 2 \int_0^\infty tW(t)\,dt / \left[ \int_0^\infty W(t)\,dt \right]^2 - 1
\]

\[
n = 1/\sigma^2
\]

#### 3.2.4. Power consumption of a stirrer

A power consumption of a stirrer is one of valuable parameters for scaling-up the reactor in a form of CSTR type. The net power (excluding friction and inertia) delivered to the reacting mixture was measured by a dynamometer. The stirrer motor could rotate freely and its speed was controlled by a variac. A selectable diameter disk (10–50 mm) was fixed on the motor. A force gauge (Lutron: model FG-5000A) with a small diameter nylon thread was used to measure a reaction force of the motor (reading resolution = 0.01 N and measured force ≈ 0.5–30 N). A tachometer (Digicon: model DT-240P) was used to measure a rotational speed of the motor (reading resolution = 0.1 rpm). The power consumption of a stirrer was calculated by the following equation.

\[
P = 2\pi NFr/60
\]

where P is the power consumption (W); N is the rotational speed (rpm); F is the reaction force (N); and r is the radius of the disk (m).

Power consumptions of a stirrer were measured at upper and lower limits of experimental flow rates (residence times of 3 and 12 min) in the speed range of 100–800 rpm. The measurement was repeated three times for each condition. Results showed that there was no significant difference of the power consumption of a stirrer for both flow rates. The higher stirrer speed significantly consumed more power. At stirrer speeds of 200, 300, and 500 rpm, power

---

**Table 1**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>NaOH 0.75%, 12 min (purity of ME = 97.5 wt%)</th>
<th>NaOH 1.0%, 6 min (purity of ME = 97.5 wt%)</th>
<th>NaOH 1.0%, 12 min (purity of ME = 99.2 wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98.4</td>
<td>95.7</td>
<td>94.2</td>
</tr>
<tr>
<td>2</td>
<td>96.5</td>
<td>96.2</td>
<td>94.3</td>
</tr>
<tr>
<td>3</td>
<td>97.0</td>
<td>96.1</td>
<td>93.6</td>
</tr>
<tr>
<td>Average</td>
<td>97.3</td>
<td>96.0</td>
<td>94.0</td>
</tr>
<tr>
<td>SD</td>
<td>1.0</td>
<td>0.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Fig. 4.** Effect of NaOH concentration on production performance of the 6-stage continuous reactor subjects to molar ratio of methanol to oil of 6:1 and temperature of 60 °C.
consumptions of a stirrer per unit volume of the reactor were 0.2, 0.6, and 2.8 kW/m³, respectively.

3.3. Quality of produced palm ME

To ensure the quality of produced ME, the sample of ME was prepared and tested its important fuel properties. The sample was prepared by transesterification in the 6-stage continuous reactor at the following selected production condition: molar ratio of methanol to oil of 6:1, inlet reactant temperatures of 60 °C, NaOH of 1.0 wt% of oil, residence time of 6 min, and stirrer speed of 300 rpm. The product discharged from the reactor was immediately washed by water to stop the reaction, further washed until it was clean, and kept for one week to obtain the complete phase separation by gravity settling. The prepared ME was analyzed by TLC/FID in which its purity was 97.6 wt%. The sample was then sent to test important fuel properties at Fuels & Lubricants Research Department, PTT Research and Technology Institute, PTT Public Company Limited, Thailand. Test methods and obtained results are shown in Table 2. In this table, fuel properties of ME are also compared with Thailand’s regulations for biodiesel, low-speed diesel, and high-speed diesel. All tested properties met Thailand’s regulations for biodiesel and low-speed diesel. Most properties met Thailand’s regulation for high-speed diesel fuel except viscosity, density, and pour point; however, they were very close to the regulation.

4. Conclusion

The designed 6-stage continuous reactor (2.272 l) for transesterification of RBD palm oil was evaluated its production performance and necessary parameters for scaling-up. Effects of residence time (3–12 min), stirrer speed (0–800 rpm), and NaOH concentration (0.25–1.0 wt% of oil) on the production performance were investigated at molar ratio of methanol to oil of 6:1 and temperature of 60 °C. Higher stirrer speed increased the reaction rate up to an appropriate speed but excessive stirrer speed decreased the reaction rate. Running the reactor at inappropriate stirrer speeds dramatically decreased the production capacity of the reactor. Higher NaOH concentration significantly increased reaction rate and production capacity of the reactor. The reactor had a RTD equivalent to 5.98 ideal CSTRs in series and a production performance equivalent to a plug flow reactor. At NaOH of 1.0 wt% of oil, the reactor could produce ME at purities ranging from 97.5 to 99.2 wt% within residence times of 6–12 min in which production capacities were in range of 17.3–8.5 l/h and power consumptions of stirrer were in range of 0.6–0.2 kW/m³. The developed continuous reactor has a good potential for biodiesel production industry.

Acknowledgements

Authors acknowledge the Office of the Higher Education Commission (Thailand), Prince of Songkla University, and the Joint Graduate School of Energy and Environment at King Mongkut’s University of Technology Thonburi for the scholarship and research fund provided to T. Leevijit.

References


