

A novel ultrasonic reactor for continuous production of biodiesel from waste acid oil

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(Received 5 May 2016 • accepted 11 October 2016)

Abstract—FAME was produced by a two-step in-situ transesterification of acid oil (AO) with methanol in a novel continuous flow ultrasonic reactor system composed of four ultrasonic reactors with different frequency. The hydrodynamic behavior of the reactor was investigated by a step response technique, and the effect of ultrasonic frequency on mono-alkyl esters of long chain fatty acids (FAMES) formation was also investigated. The production process includes an in-situ sulfuric acid-catalyzed esterification of AO with methanol in the first two ultrasonic reactors successively followed by an in-situ base-catalyzed transesterification in the other two ultrasonic reactors. The AO initial free fatty acids (FFA) content about 17.5 w% was cut down to less than 1 w% by sulfuric acid-catalyzed esterification. FAME yields in excess of 97.0% identified by gas chromatography/mass spectrometry (GC/MS) were obtained by the two-step in-situ reaction. The maximum and minimum volumetric productivity could reach $13.76 \text{ L}\cdot\text{h}^{-1}$ and $10.24 \text{ L}\cdot\text{h}^{-1}$ respectively.

Keywords: Novel Reactor, Ultrasonic-enhanced, Continuous Production, Biodiesel, Waste Acid Oil

INTRODUCTION

The demand for energy has increased rapidly with development of the global economy and population over the last few decades. With the fossil fuel resource depletion and environmental problems, biodiesel, called chemically mono-alkyl esters of long chain fatty acids (FAMES), is regarded as a promising substitute fuel and has been gained extensive concerns for its renewable, biodegradable, non-toxic and environmental friendly natures [1,2].

Biodiesel can be produced by methanolysis of natural triglycerides such as vegetable oils, animal fats and microalgae oils [3-6]. Refined vegetable oils have been studied intensively for biodiesel production for many years, but its price is high and accounts for about 70-85% of the biodiesel production cost, which is a major drawback to its commercialization. Therefore, it is necessary to find a way to minimize the production cost of biodiesel [7,8]. Zhang et al. [9] prepared biodiesel from acidified oil by a microwave assisted batch method and obtained methyl esters yield 97.4%. Lin et al. [10] used acid oils as feedstock for biodiesel production with a stirred tank in batch.

A side product of edible vegetable oil industry, called acid oil (AO), was usually discarded due to its high free fatty acid content. In 2014, the production of edible oil in China was about 25 million tons, which means that the potential of producing by-product acid oil (AO) was about 2.5 million tons. AO is a potential feedstock for biodiesel production due to its low price that accounts for less 20% cost of refined vegetable or edible-grade oil [11]. Using waste AO as raw material for producing biodiesel is not only favorable for material and energy conservation, but also for environmental pro-

tection by reusing waste matter, so the AO was chosen as raw material for producing biodiesel in this work.

Nevertheless, high free fatty acids (FFA) that exist in AO have a negative impact on the production of fatty acid methyl ester (FAME) in the direct alkaline-catalyzed process [12] because the free fatty acids, saponified matter, can react with alkali to form soap that would make the purification of biodiesel difficult and reduce the FAMES yield. However, in addition to serious erosion of sulfuric acid, the acid-catalyzed esterification reaction rate is slower than that of base-catalyzed esterification reaction, so the acid-catalyzed esterification reaction requires higher reaction temperature and longer reaction time to reach a high conversion rate. Thus, the biodiesel producing process from AO and methanol composed of an in-situ acid-catalyzed esterification followed by an in-situ base-catalyzed transesterification is more appropriate. Free fatty acids could first be transformed into fatty acid methyl ester by esterification with methanol at the presence of concentrated sulfuric acids catalyst, and the potential saponified matter was first reduced dramatically. To save overall production time and washing water, the acid-catalyzed reacted mixture containing few free acid and water was allowed to directly flow into the latter two ultrasonic reactors for base-catalyzed transesterification without separation.

Because acid oils and methanol are immiscible, the esterification or transesterification reaction is a diffusion controlled process [7] and can take place only on the phase boundary [13] that requires diffusive, laminar mixing rather than convective mixing for effective processing. Cavitation effects and micro-jet caused by ultrasonic irradiation could make a fine emulsion, which would significantly enhance the mass transfer and consequently accelerate the reaction rate [14,15]. On the other hand, small-scale or batch processing with ultrasonic reactor has been commonly studied for biodiesel production to date. Batch processing has several disadvantages compared to continuous processing: it requires larger reactor vol-

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umes and higher capital investment for the same production capacity; it is inherently less efficient than continuous processing owing to its start-up and shutdown nature, and there are batch-to-batch variations in the quality of the products. However, no continuous, especially pilot-scale ultrasonic-assisted biodiesel processing technical data has been available in the literature, so a novel and more efficient ultrasonic reactor system for continuous production of higher quality biodiesel was developed in this work. Power ultrasonic reactor with lower frequency is more powerful for viscosity liquid mixture of OA-methanol, so four different lower efficiencies 15 kHz, 25 kHz, 35 kHz and 40 kHz were selected; it may be also for another consideration of reverberation production in the reactors. The combination of multi-frequency ultrasonic radiation not only improves the distribution of sound energy density and increases the cavitation intensity within the reactor, but also can make sound energy distribution in the ultrasonic reactor more even because of multi-frequency reverberation effect. Thus, multi-frequency ultrasonic reactors were designed to strengthen the mass-transfer reaction process rather than using single frequency.

The objective of this work was to produce biodiesel continuously from low-cost waste acid oils by a two-step in-situ acid-catalyzed esterification followed by base-catalyzed transesterification under ultrasonic irradiation and to investigate the hydrodynamic and reaction feature of the reactor system for optimizing the operation parameters such as ultrasonic power, ultrasonic frequency, molar ratio of methanol to OA and total material flow rate in the continuous production of biodiesel.

MATERIAL AND METHODS

1. Reagents and Materials

The acid oil (AO) with high FFA contents was purchased from Dexu Trade Co. Ltd. in Guangzhou, China. The main physical properties and fatty acid composition of AO are shown in Table 1. All other chemicals used in this work were of analytical reagent grade (AR, $\geq 99.5\%$).

2. Ultrasonic Reaction and Production Set-up

Ultrasonic energy is well known as a useful tool to produce inten-

sive emulsions for immiscible liquids. Our previous research proved that the transesterification under ultrasonic irradiation can be carried out with smaller amounts of catalyst, smaller molar ratio of methanol to oil and at lower reaction temperature; higher yields of FAME were obtained in shorter reaction time compared with the mechanical stirring method. So a novel meso-scale ultrasonic reaction system for continuous production of biodiesel from acid oil

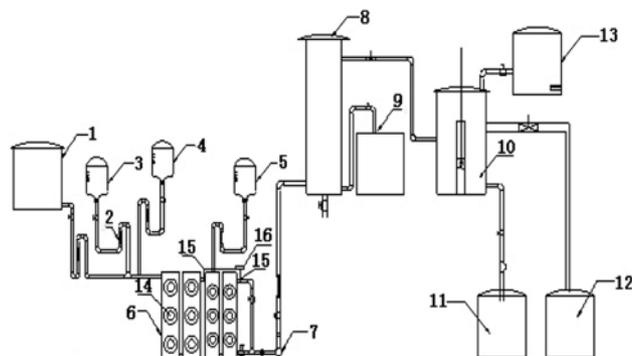


Fig. 1. Multi-frequency combined ultrasonic reactor system for continuous biodiesel production.

- | | |
|----------------------------|----------------------|
| 1. Oil tank | 9. Raw glycerol tank |
| 2. Flow meter | 10. Washing tank |
| 3. Methanol tank | 11. Wastewater tank |
| 4. Sulfuric acid tank | 12. FAMES tank |
| 5. Methoxide solution tank | 13. Hot water tank |
| 6. Ultrasonic reactors | 14. Transducer |
| 7. Oil pump | 15. pH electrode |
| 8. Glycerol separator | 16. Recorder |

Table 1. Main physical properties and fatty acid composition of AO

Parameter	Unit	Average \pm SD ^b
Density (20 °C)	$\text{g}\cdot\text{cm}^{-3}$	0.8890 \pm 0.02
Viscosity (40 °C)	$\text{mm}^2\cdot\text{s}^{-1}$	7.79 \pm 0.02
Acid value (AV)	mgKOH/g	33.42 \pm 0.12
Saponification value (SV)	mgKOH/g	247.28 \pm 0.13
The average molecular weight	$\text{g}\cdot\text{mol}^{-1}$	786.96 \pm 0.34
Myristic acid (C _{14:0}) ^a	wt%	0.93 \pm 0.01
Palmitoleic acid (C _{16:1})	wt%	1.77 \pm 0.12
Palmitic acid (C _{16:0})	wt%	24.76 \pm 0.50
Linoleic acid (C _{18:2})	wt%	16.32 \pm 0.41
Oleic acid (C _{18:1})	wt%	48.85 \pm 0.53
Stearic acid (C _{18:0})	wt%	7.37 \pm 0.25

^aCarbon atoms number: double bonds number

^bSD: one standard deviation

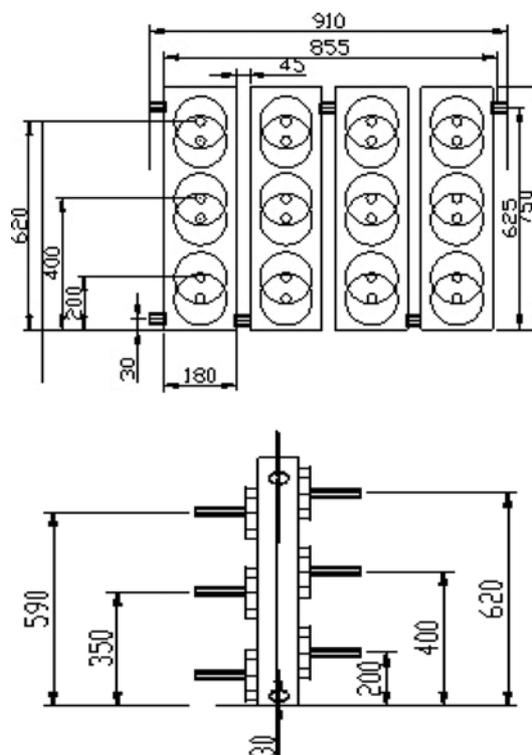


Fig. 2. Geometric construction of ultrasonic reactor and the layout of transducer.

was developed in this work, shown in Fig. 1.

The reaction system working volume is about 22 L, which consists of four ultrasonic reactors connected in series. Each ultrasonic reactor equipped with jacket for temperature control is a narrow rectangular body (valid length 0.16 m, width 0.05 m, height 0.70 m) made of stainless steel plate as shown in Fig. 2. The ultrasound propagating in each reactor is produced by frequency of 15 kHz, 25 kHz, 35 kHz and 40 kHz piezoelectric transducer (diameter 0.12 m, made of titanate lead-zirconate), respectively. Each ultrasonic transducer on the reaction tank is controlled independently by a switch. So every ultrasonic transducer can work alone or in combination with another. Each reactor has six transducers which are equally stuck to two face-to-face flanks of the reactor and supplied by a generator with input power ranging from 0 to 500 W. As shown in Fig. 2, the transducers on one flank have eccentric distance equating the radius of the transducers relative to those on the other flank, so the sound inactive region is as minimized as possible. The ultrasound propagates through the oil in the direction perpendicular to the oil flowing, which causes intensive transverse mixing of the reactants rather than convective mixing. The first two reactors are for acid-catalyzed pre-esterification and the other two reactors for transesterification following the acid-catalyzed pre-esterification.

3. Experimental Procedures

As mentioned, acid oil (AO) is unfavorable for the directly base-catalyzed transesterification reaction. It must be pre-esterified with methanol in the presence of sulfuric acid to cut FFA to less than 1% weight of oil in the first two ultrasonic reactors. Subsequently, the pre-esterified mixture was used as starting material for transesterification reaction with methanol and catalyst of anhydrous potassium hydroxide to produce FAMES in the latter two ultrasonic reactors.

3-1. Acid-catalyzed Pre-esterification

The acid oil and methanol flowed into the first two reactors at given molar ratio of methanol to oil, mass ratio of sulfuric acid to oil, and temperature of 60. The pre-esterification of AO with methanol at the presence of concentrated H_2SO_4 was carried out for a period of time that allowed steady-state conditions to be reached with each reactor input power of 200 W. Samples of pre-esterified were taken at the outlets of the second reactor at given intervals, and then neutralized immediately with alkali solution for analysis. After pre-esterification, the AV of the oil dropped to less than 1% and the yields of FAME increased simultaneously, and thereby saponification potential can be reduced or eliminated.

3-2. Base-catalyzed Transesterification

The pre-esterified oil flowed smoothly into the latter two ultrasonic reactors where transesterification was carried out in the presence of anhydride alkali with each reactor input power of 200 W for a certain time. All experiments were run for at least 4 vol replacements to ensure steady state conditions had been achieved. A series of consecutive runs would allow the system to completely flush out the material from the previous run and come to steady-state conditions. Then, ten milliliters of samples were taken from the exit of the fourth reactor in prescribed time intervals and immediately neutralized by the addition of 5% phosphoric acid aqueous solution to stop the reaction. The samples were left to settle for 3 h for phase separation before analysis. The upper layer mainly containing biodiesel was washed with distilled water for three times to remove

impurities and then dried in vacuum dryer at 100 °C. Then 0.1000 g of biodiesel product was diluted to 10% mass fraction with n-hexane for gas chromatography/mass spectrometry analysis.

4. Analysis

FFA content was determined by standard titrimetry method according to EN 14104 Standard. The disposed sample was dissolved in 50 ml ethanol/ diethyl ether mixture (1 : 1), and the solution of 0.1 M KOH dissolved in ethanol was used as titrant. The indicator was phenolphthalein solution. FFA content is in proportion to AV.

The FAME yield was calculated from the weight of FAME in the FAME phase and the theoretical material balance of the transesterification reaction by Eq. (1):

$$\text{FAME yield (\%)} = \frac{w_{\text{FAME}}/M_{\text{FAME}}}{3w_{\text{AO}}/M_{\text{AO}}} \times 100 \quad (1)$$

Gas chromatography/mass spectrometry (GC/MS-QP2010, SHIMADZU Co., Ltd., Japan), equipped with DB-1 capillary column (27 m×0.25 mm×0.25 μm) and FID detector, was used for analyzing the FAME content of the product. The oven temperature of GC was held at the initial temperature of 50 °C for 3 min, and heated to 180 °C at the rate of 10 °C/min and held for 10 min, and then ramped to a final temperature of 290 °C at the rate of 20 °C/min, held for 10 min, and the total run time was 41.5 min. The injector temperature was set at 290 °C, while the detector temperature was set at 300 °C. Helium gas was used as carrier gas with a flow of 1.23 mL/min. The product was also analyzed by the recommended methods of National Standard of the People's Republic of China (GB/T 20828 -2007).

RESULTS AND DISCUSSION

1. The Features and Hydrodynamic Behaviors of the Reactor

In continuous flow mode, the FAME yield is closely related to the reaction kinetics and hydrodynamic behavior of the reactor, which determine the contact time and degree of mixing in reactants. The hydraulic behavior can be quantified by residence time distribution (RTD) of the reactors. The overall RTD of the first two ultrasonic reactors in series at total flow rate of 12 L/h was measured by a step response technique under different input ultrasonic power radiating. Initially, the ultrasonic reactors were charged with refined oils with AV about 1.0 mgKOH/g, after a steady state reaching, acid oils with AV about 33.4 mgKOH/g was used as the feed to displace the refined oils. The pre-experiment results show that, without methanol and catalyst, the AV of oil was almost kept a constant under ultrasonic radiation, so using AV as tracer is reliable. The flow rates of acid oil were kept constant, the AV of the effluent at the exit of the second reactor was measured and depicted in Fig. 3. The experimental curves of RTD show that the input ultrasonic power obviously influences the RTD: As input power increases, the shape of RTD curves becomes narrower and move forward to ordinate, which is interpreted as that the difference between theoretical average residence time and experimental residence time gets smaller and dimensionless residence time standard deviation becomes smaller. These may be attributed to fine transverse mixing of reactants in cross section area of the reactor owing to intensive cavitation effect caused by propagating of ultrasound through the reactants which flowed

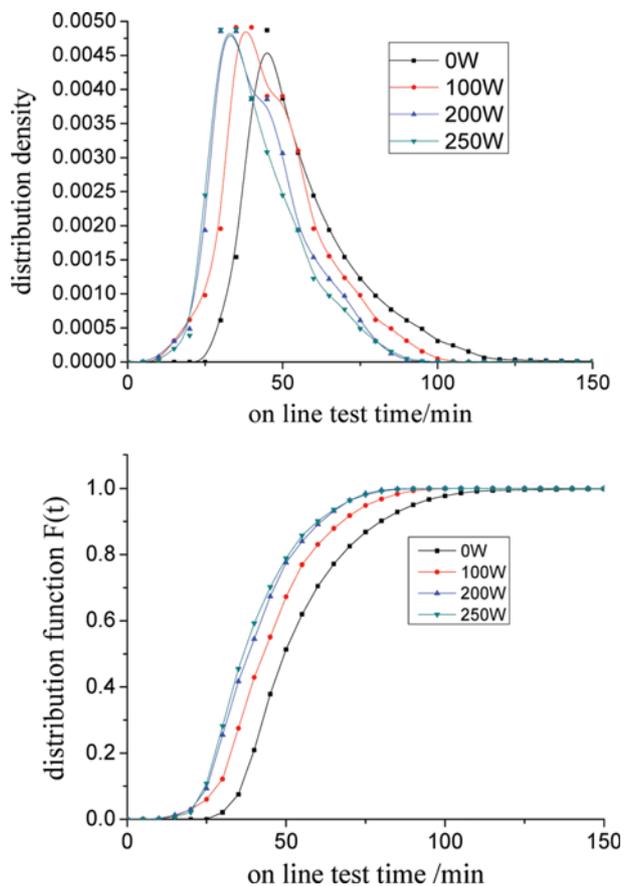


Fig. 3. Experimental responses of the reactor to inlet stimuli at the second reactor exit with ultrasonic or without ultrasound radiation: $Q=12$ L/h.

in the direction normal to the ultrasound transmission. Higher and more uniform energy distribution due to reverberation of ultrasound and shorter ultrasound transmission path in the reactors may be another important reason for intensive mixing of the reactants. After 200 W, a further increase in input power has not significant effect on the shape of RTD because the bubbles shielding effect induced by excessively high input power hinders the effective radiation energy transmission into the reactors; consequently, the mixing becomes weaker.

2. The Effect of Ultrasound Frequency

To investigate the effect of ultrasonic frequency on the formation of methyl ester, first, one frequency ultrasonic reactor worked alone, then four frequency ultrasonic transducers were switched on simultaneously to work in multiple-frequency combination. A series of experiments were carried out under the following conditions: each reactor input power of 200 W, the catalyst usage of 1.4 wt%, molar ratio of alcohol to oil 8:1 and reaction temperature of 40 °C, the total flow rate of 6 L/h with the residence time through a single ultrasonic reactor was selected. Samples were collected at a given interval as soon as steady state had arrived and then prepared for analyzing. The results in Fig. 4 show methyl ester mass fraction that transesterification of pre-esterified AO with methanol was about 79.80% at the frequency of 15 kHz, 90.74% at the frequency of 40 kHz. This result can be explained as that the increase of ultrasonic

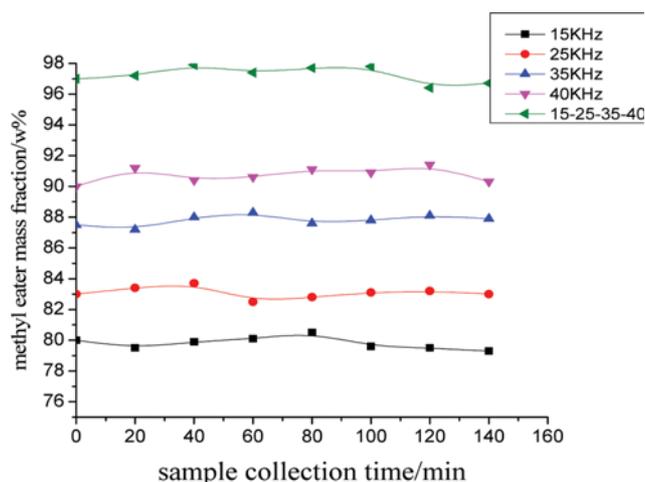


Fig. 4. Effect of single frequency and multi-frequency ultrasonic radiation on methyl esters yield.

frequency can provide more energy and greater sound intensity distribution. So, that is conducive to the mass-transfer reaction within the system. Then, the effects of multi-frequency ultrasonic radiation on FAME yields were investigated. The results shown in Fig. 4 indicate that methyl ester mass fraction was about 97.26% in the combination of multi-frequency (15+25+35+40 kHz) ultrasonic radiation. Compared with the results in signal-frequency ultrasonic radiation (40 kHz), the methyl ester mass fraction increased by 6.52%. The reason may be that the different sized cavitation bubbles in oil mixture can be made resonant response in the combination of multiple-frequency ultrasonic radiation. It not only strengthens the cavitation effect and makes the acoustic field distribution more even, but also increases the bubbles' specific surface area and speeds up update of the interface, further to enhance the mass transfer reaction. Furthermore, the two opposite transducers with the same frequency may form similar to sine wave whose peaks and troughs can compensate for each other, which can make the sound intensity distribution in the reactor more stable and larger. Therefore, in this work, we chose the multiple-frequency combination of ultrasonic radiation. To realize continuous production, we proceeded for pre-esterification reaction in the first two reactors and for esterification reaction in the latter two reactors.

3. Acid-catalyzed Pre-esterification Behavior of the Reactors

3-1. The Effect of Input Power

To investigate acid-catalyzed esterification behavior of the reactors at 60 °C, a series of in-situ acid-catalyzed esterifications of AO were carried out at mass ratio of sulfuric acid to oil 1.6%, molar ratio of methanol to oil 8:1 and total flow rate 12 L/h in the first two ultrasonic reactors with four-frequency combination 15 kHz+25 kHz+35 kHz+40 kHz radiation and different input power. After four volume replacements, samples were collected from the exit of the second reactor and then dealt with for analyzing AV. The effect of input ultrasonic power on the esterification behaviors of the reactors is shown in Fig. 5. The data shows that input ultrasonic power dramatically influences the rate of esterification reaction of AO with methanol. The rate can significantly be accelerated for the reason that the values of free fatty acid of the pre-esterified oil

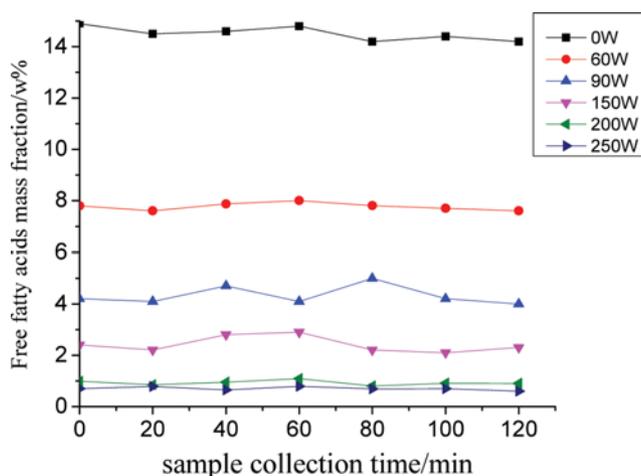


Fig. 5. Effect of ultrasonic power on the acid value of the pre-esterified mixture at the second reactor exit.

were remarkably reduced to less than 1 w% as soon as ultrasonic had been switched on. The reason may be that cavitation and micro-jet in the immiscible liquid mixture induced by ultrasonic radiation intensively disturbs the flowing condition as well as inter-phase boundary which consequently makes the mixture uniformly emulsified and deeply enhances the mass transfer in the immiscible liquid mixture that speeds up the rate of esterification of esterification of AO with methanol. However, further increasing ultrasonic power up to 250 W made little acceleration of the esterification rate; this may be ascribed to the fact that abundant cavitation bubble formation due to excessive input power induces “bubbles shielding” near the radiating surface that impedes the acoustic energy transmission into the mixture and caused methanol excessively evaporating.

3-2. The Effect of Flow Rate

A series of experiments of the effect of reactant mixture flow rate on the esterification were performed under the conditions of each reactor input power 200 W, the temperature of 60 °C, and molar ratio of methanol to AO 8 : 1, mass ratio of concentrate sulfuric acid

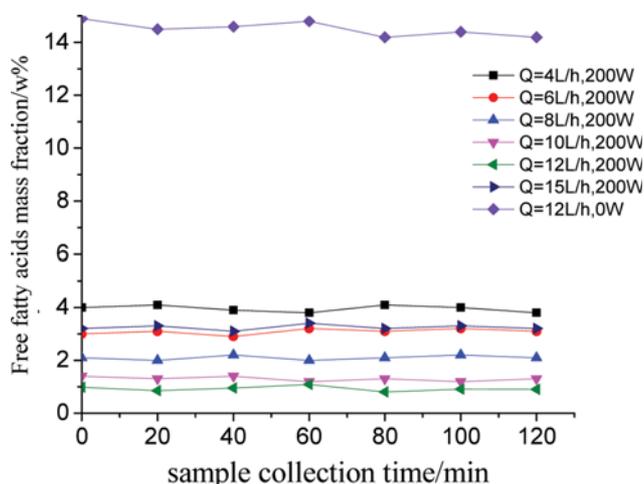


Fig. 6. Effect of flow rate on the on the acid value of the pre-esterified mixture at the second reactor exit.

to AO 1.6% to find the maximum capacity for a given system. The results are shown in Fig. 6. When the total flow rate of the mixture of AO and methanol and catalyst was increased from 4 L/h to 12 L/h corresponding to residence time for esterification reduced from 165 mins to 55 mins, the average free fatty acid of the esterified oil was decreased from 4.1% to 0.98% (w%). This result indicates that proper residence time is favorable for high conversion of free fatty acid to ester because esterification is a reversible reaction. When the total flow rate is 4 L/h, the residence time of 165 mins is too long for AO conversion which is favorable for backward reaction due to the product of water accumulation, so the conversion of AO is the lowest. However, the residence time of 44 mins corresponding to total flow rate of 15 L/h is not adequate for esterification to be fully carried out, so the conversion of AO is poorer and the final free fatty value remained about 3% (w%).

4. Alkaline Catalyzed Transesterification

4-1. The Effect of Input Power

The pre-esterified oil mixture from the second reactor orderly flowed into the latter two reactors for continuous production of methyl ester by transesterification with methanol at presence of potassium hydroxide catalyst. The experiments were performed using different input power at the mass fraction of potassium hydroxide to the oil 1.4%, the mole ratio of methanol to AO 8 : 1, the temperature of 40 °C and total flow rate of 12 L/h. Samples were collected and prepared for analysis at a given interval as soon as steady state had arrived, and the results are shown in Fig. 7. The results indicate that the mass fraction of methyl ester in products increases with rise of input power, because cavitation and consequent disturbing became more violent along with the increase of input power. Then the mass transfer in the reaction system was intensively enhanced and transesterification was performed more fully.

4-2. The Effect of Residence Time

The residence time is a key factor in obtaining high quality methyl ester product and optimizing production capacity of a given plant. A series of experiments at different total flow rate were carried out under the following conditions: mass fraction of potassium hydroxide to refined oil 1.4% (w%), the mole ratio of methanol to AO 8 : 1,

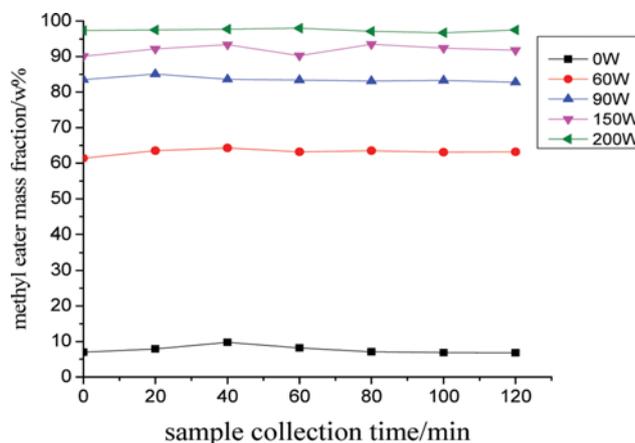


Fig. 7. Effect of input power on methyl esters yield in the process of transesterification.

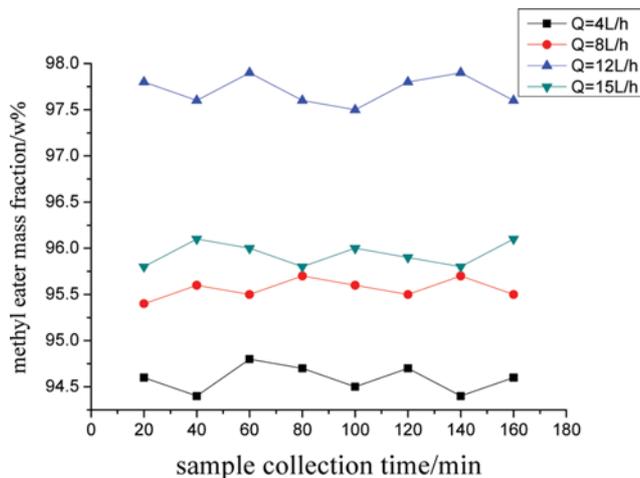


Fig. 8. Effect of flow rate on methyl esters yield in the process of transesterification.

the temperature of 40 °C and each reactor input power of 200 W. The results in Fig. 8 indicate that the average mass fraction of methyl ester in products is below 95% at residence time of 165 mins corresponding to total flow rate of 4 L/h; it does not meet the EU standard which requires methyl ester contents at least 96.5%. Long residence time is unfavorable for formation of FAME because transesterification is a reversible reaction; and the accumulation of its byproduct of glycerol would promote the backward reaction, then reduce the methyl ester formation. When residence time decreases, the mass fraction of methyl ester increases and reaches above 97.5% at residence time of 55 mins corresponding to total flow rate of 12 L/h. Further decreasing residence time to about 42 mins corresponding to total flow rate of 15 L/h makes the methyl ester mass fraction diminish below 96%, which suggests that 42 mins residence time is too short for transesterification of oil with methanol fully. During long time continuous operation, the reaction system displays steady behavior in the light of product profile and methyl ester yields, which indicates that the novel reaction system for biodiesel production is effective and practical.

4-3. Calculation of Volumetric Productivity

We defined Eq. (2) to calculate the volumetric productivity of the system under the experimental conditions.

$$V_p = \frac{V}{t} \quad (2)$$

We could calculate the system volumetric productivity of biodiesel

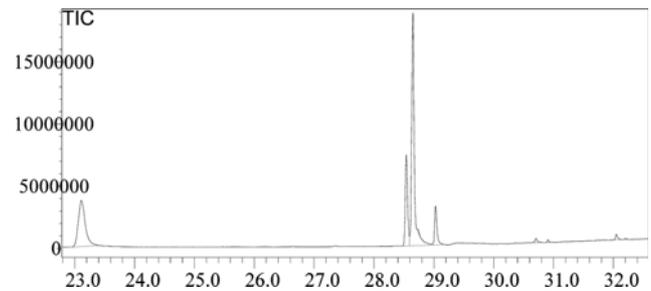


Fig. 9. The FAME chromatogram of biodiesel produced by the reactor.

at different flow rate using Eq. (2). The properties parameters of FAME can be obtained from Table 2. Taking into account the EU standards for biodiesel quality that the content of fatty acid methyl esters cannot be less than 96.5%, the maximum and minimum biodiesel volumetric productivity are 13.76 L·h⁻¹ and 10.24 L·h⁻¹, respectively.

5. Production Analysis

As shown in Fig. 9, the total ion current chromatogram of biodiesel products indicates that the four main compounds in the biodiesel are methyl hexadecanoate, methyl linoleate, methyl oleate and methyl stearate, respectively, and FAME yield achieves about 97.6% at residence time of 55 mins corresponding to total flow rate of 12 L/h, mass ratio of potassium hydroxide to oil of 1.4%, the temperature of 40 °C and each reactor input power of 200 W. This shows a high yield of FAME in the novel ultrasonic reaction system.

Each property of production was compared with biodiesel standards (GB/T20828-2007S50). As shown in Table 2, almost all of physical properties are in reasonable agreement with GB/T20828-2007S50.

CONCLUSIONS

The production of biodiesel from low-cost acid oil (AO) by a two-step in-situ transesterification of acid oil (AO) with methanol is applicable. The novel ultrasonic reaction system is practical and effective because the average initial acid value of AO can be reduced from 17.5 w% to less than 1 w% by a concentrated sulfuric acid catalyzed-esterification with methanol under the optimum conditions: each reactor input power of 200 W, the mass ratio of concentrated H₂SO₄ to AO 1.6%, the molar ratio of methanol to AO 8 : 1, total residence time of 55 mins and the reaction temperature of 60 °C. The yield of fatty acid methyl esters (FAME) in excess

Table 2. Properties of production in comparison with the GB/T

Property	Testing results	Testing procedure	Standards GB/T20828-2007S50
Viscosity at 40 °C (mm ² /s)	5.544	GB/T 265-1988(2004)	1.9-6.0
Density at 20 °C (g/cm ³)	0.8824	GB/T 1884-2000(2004)	0.820-0.900
Close-flashing point (°C)	159.0	GB/T 261-2008	≥130
Cetane index	46	GB/T 11139-1989(2004)	
Net calorific value (cal/g)	9507	GB/T 384-1981(2004)	

97.0% was attained at the optimum conditions: 8 : 1 molar ratio of methanol to AO, 1.4 w% mass ratio of potassium hydroxide to AO, reaction temperature of 40 °C, each reactor input power of 200 W and total residence time of 55 mins. Taking into account the quality of biodiesel, the maximum and minimum volumetric productivity can reach 13.76 L·h⁻¹ and 10.24 L·h⁻¹.

ACKNOWLEDGEMENTS

Thanks to the Combining Project of Industry-University-Research of Guangdong Province (2011B090400116), and Science and Information Technology Bureau of Guangzhou of China for funding this work, and the South China University of Technology for testing supports.

NOMENCLATURE

- w_{FAME} : weight of FAME in the FAME phase [g]
 w_{AO} : weight of AO used [g]
 M_{FAME} : average molecular weights of the FAME [g·mol⁻¹]
 M_{AO} : average molecular weights of the AO [g·mol⁻¹]
 V_p : the volumetric productivity of reactor [L·h⁻¹]
 V : the volume of production biodiesel [L]
 t : time of production biodiesel [h]

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