The Performance Testing of Biodiesel Oil Produced from Waste Cooking Oil by Using a Prototype Solar Reactor for Agricultural Diesel Engines

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Received 8 August 2019; Revised 20 August 2019; Accepted 21 August 2019

Abstract

Biodiesel oil is one of the liquid fuels that generally employed with small agricultural diesel engines. The most widely raw material for biodiesel production is waste cooking oil. This research work presented the biodiesel production from waste cooking oil with a prototype solar reactor and testing the obtained oil both in terms of physicochemical properties following the EN14214 and ASTM D6751standard method and performance testing of engines. The results found that the final biodiesel product can be accepted within the requirements standard of bio-auto fuels such as methyl ester content, kinematic viscosity, pour point and cloud point. Additionally, a single-cylinder diesel engine was employed to test the performance of biodiesel oil and comparison with diesel oil. The data found that exhaust gases emission namely CO_2, CO, HC, and NO_2 a trend was lower than petroleum diesel oil. While the performance testing of engines displayed, both of the biodiesel oil and diesel oil was not different. Thus, waste cooking oil derived biodiesel oil has an efficiency, suitability, and possibility to apply for the real application with the small agricultural diesel engines to substitute the use of petroleum diesel oil.

KEYWORDS: Biodiesel oil; Agricultural diesel engines; Waste cooking oil; Solar reactor
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Introduction

Biodiesel is generally known to be a liquid fuel for substitution petroleum diesel fuel due to they can be directly used in diesel engine especially agricultural diesel engines. Normally, biodiesel is a long chain fatty acid mono–alkyl ester (methyl ester or ethyl ester) which was synthesized with converting fatty acid triglyceride by transesterification reaction against small molecule of alcohol such as methanol or ethanol in the presence of a catalyst [1 – 4]. Several sources of vegetable oil (both edible and non–edible), animal fat and waste cooking oil have been not only brought to study as a raw material for biodiesel production in the laboratory but also attempted to scale up production for the community enterprise and industrial scale. Since the physicochemical properties of the biodiesel product has high quality and resembles the properties of diesel oil, then they are promoted to use both pure biodiesel oil (B100) and blending together with petroleum diesel oil, for example, B10, B15, and B20 (the ratio of biodiesel oil against diesel oil as 10:90, 15:85 and 20:80, respectively) [5 – 7].

The raw material of biodiesel production has several potential sources especially palm oil, coconut oil, waste cooking oil, animal fat, jatropha oil, soybean oil, and rapeseed oil [8, 9]. Focus on Thailand which is biodiversity and agricultural country, there is feedstock oil to produce biodiesel as the top of the world particularly palm oil material. However, the only use of palm oil maybe not sustainable due to they are an important raw material for the general consumption, food industry, and cosmetic industry which directly caused competition between edible oil consumption and energy demand [9]. Therefore, waste cooking oil was interested as a high potentiality feedstock for biodiesel production particularly in rural areas of Thailand that has a lot of the oil in the household.

Several reports found that biodiesel oil derived from waste cooking oil can be used with the diesel engine and mostly considered from the physicochemical properties that only tested in the laboratory. Chaiburi, C. et al., (2010) found that the testing small diesel engine by used biodiesel from jatropha oil with analysis at any time until 2 hours gave the results involving the amount of CO gas less than using petroleum diesel oil [10]. Asavatesanupap C. and Klansiri, S. (2014) reported about performance evaluation of biodiesel product derived from refined palm oil (RPO) with a single-cylinder diesel engine. The results showed that the blending biodiesel B10 and B50 were similarly performance versus conventional diesel oil but biodiesel product demonstrated lower gases pollution emission [11]. Poompipatpong, C. et al., (2015) investigated the performance of a small fisher boat's engine fueled with biodiesel B20 for 500 h operation. The studies have found that biodiesel B20 does not damage the engine and performances slightly decreased after the 500 h operation. Hence, this work can be concluded that biodiesel B20 possibly used to the real application for a small engine [12]. Phasinam, K. and Arjharn, W. (2016) studied the performance and pollution of a medium-speed diesel engine by using a commercial biodiesel fuel which certified by the Department of Energy Business, Ministry of Energy, Thailand. They found that all of the engines applied with biodiesel B20 showed better performance or similarly against petroleum diesel oil. Additionally, the emission exhaust gas namely CO and SO_2 have a decreasing trend compared with conventional diesel oil [13].

Therefore, the objective of this work is to evaluate the performance of biodiesel oil which was produced from waste cooking oil as a raw material. The novelty of this work is the use of a prototype solar reactor to produce the biodiesel product and focus on the use of biodiesel oil B100 with an agricultural diesel engine which was a single-cylinder diesel engine and compared against petroleum diesel oil. In addition, the physicochemical properties of the biodiesel product (B100) and petroleum diesel oil were investigated and presented in this report following the European Standard methods (EN14214) and American Society for Testing and Material (ASTM D6751) methods. Finally, the obtained biodiesel product was used with real agricultural diesel engines by plowing to prepare the soil for cultivation in the rural area of Sakon Nakhon province, Thailand.

Materials and Methods

Materials

Waste cooking oil as raw material with the amount of free fatty acid of 0.78 mg KOH/g of oil and moisture 0.7 wt.%, was purchased from the local market in Mueang Sakon Nakhon District, Sakon Nakhon Province, Thailand. Methanol (CH_3OH) and hexane (C_6H_{14}) commercial grade with purity 95% were purchased from S-C SCIENCE Co., Ltd, to be used as a reagent and solvent. NaOH commercial grade was used as a catalyst obtained from S-C SCIENCE Co., Ltd. The TLC plate (Silica Gel 60 F254) was bought from Merck, Darmstadt, Germany. Petroleum ether and diethyl ether analytical reagent grade purchased from ANaPURE Co., Ltd, and glacial acetic acid obtained from QRëC Co., Ltd, were applied as a developing solvent for monitoring the conversion progress of waste cooking oil to biodiesel product.

Biodiesel production from waste cooking oil

Fig. 1(a) displayed an overview of the process biodiesel production by transesterification reaction of waste cooking oil performed by using a prototype solar reactor. The reaction conditions consisted of methanol to oil molar ratio of 6:1 and NaOH as a catalyst was loaded amount of 0.5 wt.% compared with the weight of oil. The reaction mixture was sampled every 15 min of reaction time to teste the conversion progress of waste cooking oil to biodiesel product. The reaction progress was proved by TLC technique followed the method of Supamathanon, N. et al., 2011 [14]. The ratio of developing solvent was 85:15:1 v/v/v of the mixture petroleum ether, diethyl ether, and glacial acetic acid, respectively. After separation of reaction mixture complete by TLC technique, the TLC plate was dried and perfumed with iodine vapor for staining and indicating the spot of the sample as depicted in Fig. 1(b).

After the reaction completed (in this case is 1 h of reaction time), the mixture product was separated between biodiesel oil and glycerol (by-product). Then, the obtained biodiesel product was extracted by hexane and cleaned up with water to eliminate NaOH as a catalyst and soap. Finally, the biodiesel product was heated at 110 °C for 1 h to remove the excess water or moisture. After the purification process, the final biodiesel product was evaluated the physicochemical properties according to the European Standard methods (EN14214) and American Society for Testing and Material (ASTM D6751) methods for bio-auto fuels of diesel-engine such as kinematic viscosity, oxidation stability, methyl ester content which evaluated by GC and ^{1}H-NMR, pour point and cloud point [15 – 17].

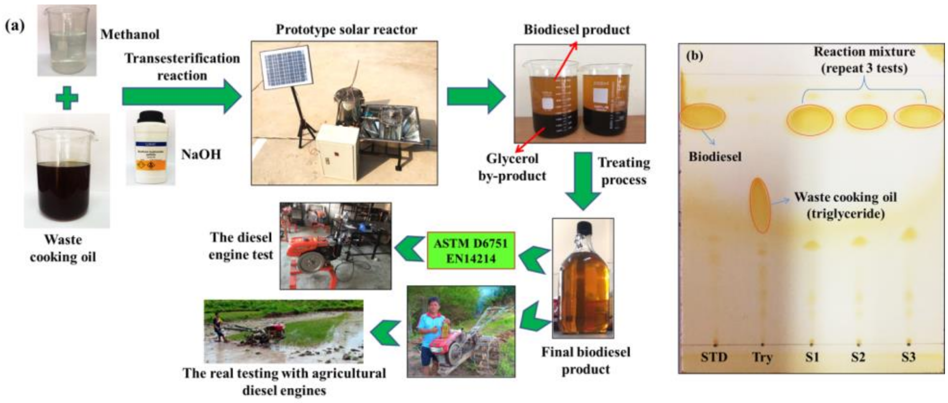


Fig. 1 (a) the process diagram of biodiesel production by transesterification reaction of waste cooking oil and the use of a prototype solar reactor. (b) TLC plate of the conversion progress of waste cooking oil to be biodiesel product.

The engine test by using diesel oil and biodiesel oil

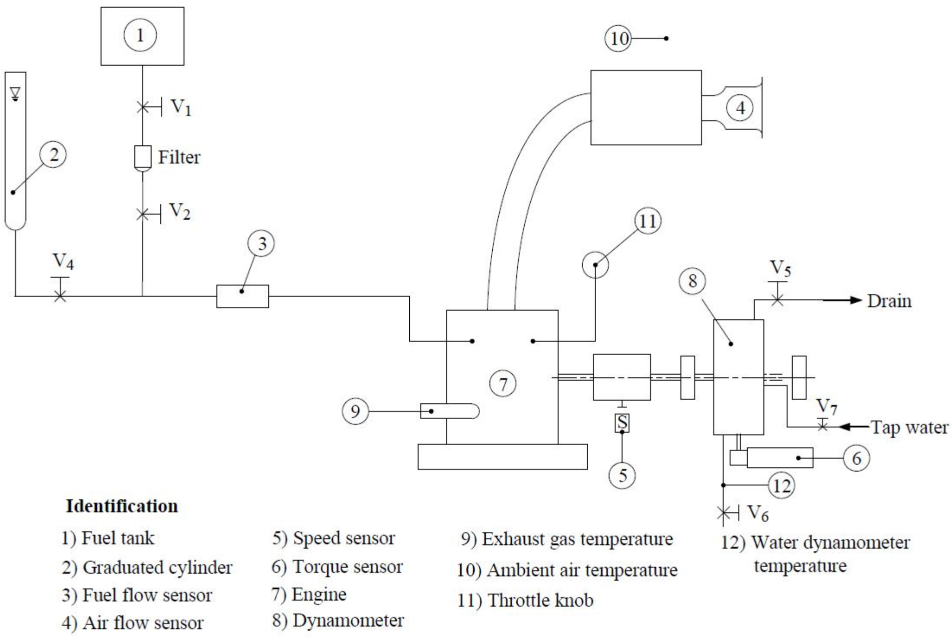


Fig. 2 schematic diagram of the engine test by using diesel oil and biodiesel oil obtained from waste

The engine used in the experiment for this research was an ignition engine with compression of Kubota RT100 which was a four-stroke and single-cylinder diesel engine. The air and fuel injection were directly brought into the system of the combustion chamber. The schematic diagram of the engine test by using diesel oil and biodiesel oil was illustrated in Fig. 2. dynamometer and it can receive the power up to The performance test of the single-cylinder hydraulic engine (MT 502HD SINGLE CYLINDER DIESEL ENGINE TESTBED, Water Absorber) was employed for measuring torque and power of the engine that a torque can increase up to 110 Nm of torque 5 kW at a maximum speed of 8000 rpm. Tachometer (DIGICON Model DT-240P) was used to measure engine speed in order to be able to determine the engine cycle at different values to be stable according to the testing standards. Flue Gas Analyzer (EMS Model 5003) was applied to determine the pollution gases from engine combustion namely HC, CO, CO_2, and NO_2. The testing of engine performance was the ISO 1550-2002 Internal Combustion Engine Determination and Method for the Measurement of Engine Power (ISBGS, 2002) to refer the determining engine work in wear testing. Diesel fuel for the engine testing in this work was ultra-low sulfur diesel Ministry of Energy, Thailand.

Results and Discussion

Physicochemical characterization of the biodiesel product

Methyl ester content

In this research, fatty acid methyl ester compositions have analyzed both gas chromatography (GC) and proton nuclear magnetic resonance spectroscopy (^{1}H-NMR) as presented the GC chromatogram and ^{1}H-NMR spectrum in Fig. 3 (a) and (b), respectively. FAME is one of the important parameters for

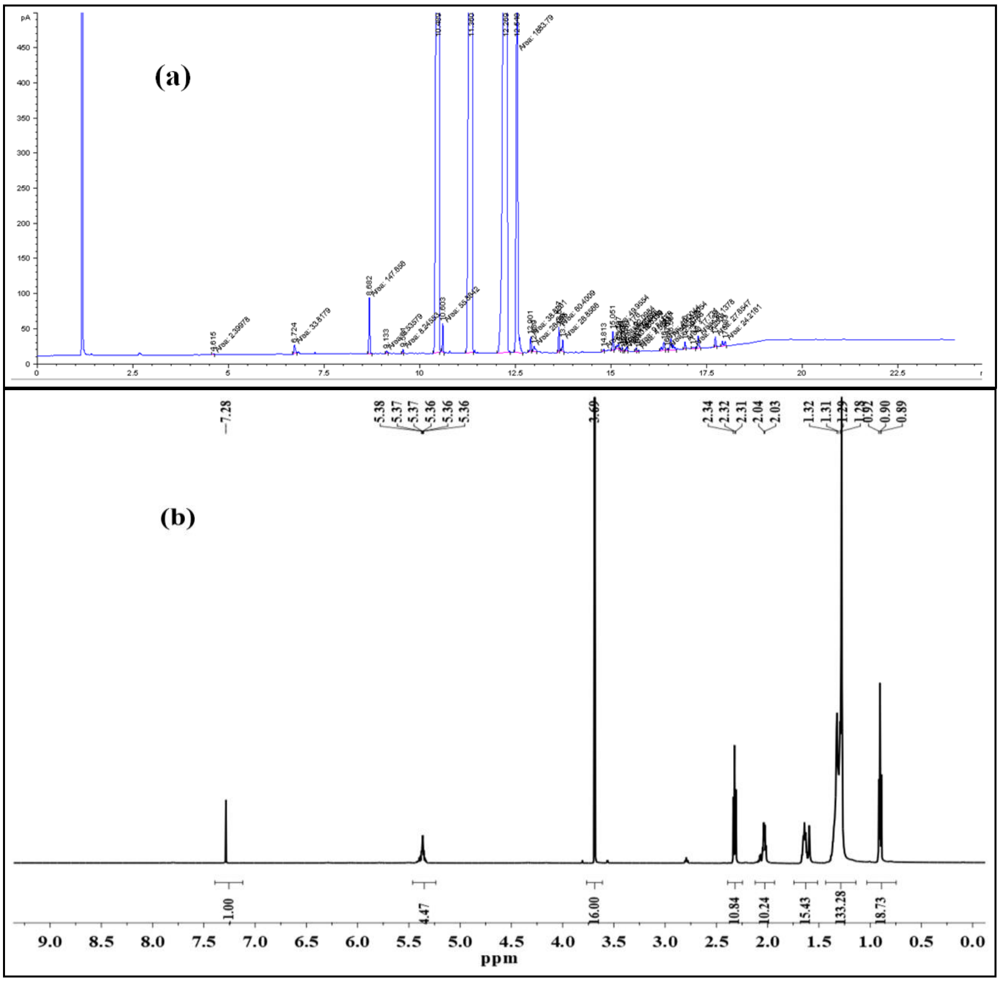


Fig. 3 (a) GC chromatogram of fatty acid methyl esters (FAME) of the biodiesel product derived from waste cooking oil and (b) ^{1}H-NMR spectrum of waste cooking oil biodisel.

physicochemical properties of the biodiesel product that directly affected to other properties. According to the EN14214 and ASTM D6751 standard methods for bio-auto fuels of diesel-engine, the FAME must be methyl ester content minimum of 96.5%. In this case, the obtained biodiesel product derived from waste cooking oil reacted with a prototype solar reactor had shown that the FAME yield was more than 97% from the use of GC technique analysis and confirmed by ^{1}H-NMR technique. This result indicated that waste cooking oil derived biodiesel product was to be the international standard for biodiesel fuel.

Kinematic viscosity at 40 °C

Table 1 summarized the major fuel properties of the synthesized biodiesel product that reference the method following the reports of Chavan, S.B. et al., 2015 [18], Knothe, G. and Razon, L., 2017[19], Roschat, W. et al., 2018 [1], Giakoumis, E.G. and Sarakatsanis, C.K., 2018 [20] and Keera, S.T. et al., 2018 [5]. Viscosity is quite an important factor for the real apply in the engine due to its meaning the liquid fuel flow to the combustion chamber which would have a great effect on torque and power of the engine [5]. The results found that kinematic viscosity at 40 °C has values in the range of 3.5 – 5.0 cSt which acceptable for standard biodiesel. However, the comparison biodiesel oil against petroleum diesel oil indicated that biodiesel oil has high viscosity than petroleum diesel oil. This reason leads to modify biodiesel product by blending with diesel oil such as B5, B10, B15 and B20 [2, 5, 11, 12]. Even though the synthesized biodiesel product showed higher viscosity than diesel oil but the employed in a single-cylinder diesel engine especially the agricultural diesel engines did not cause a problem.

Table 1 comparison of fuel properties of biodiesel oil derived from waste cooking oil and petroleum diesel oil.

Properties	Standard biodiesel	Biodiesel derived from waste cooking oil	High-speed diesel
Methyl ester content (%) by GC[a]	96.5	97.88	–
Methyl ester content (%) by NMR	–	98.40	–
Kinematic viscosity at 40 °C (cSt)[a]	3.5 – 5.0	4.49	3.18
Density at 15 °C (kg m^{-3})[a]	860 – 900	877.5	840.2
Cloud point (°C)[b]	–3 to +12	10	<–5
Pour point (°C)[b]	–15 to +16	7	<–5
Oxidation stability (h)[a]	≥ 6	15.67	>20
Total acid number (mg KOH/g oil)[a,b]	< 0.5	0.26	<0.02

[a] European standard (EN – 14214).
[b] American Society for Testing and Material (ASTM – D6751).

Density value

The density of biodiesel product is one of the main properties for bio-auto fuels which were determined in the range of 860 – 900 kg m^{-3} at 15 °C and it has the same tendency with a kinematic viscosity. In this work, we found that the density of pure biodiesel oil was met in the range of standard limitation. When compared the biodiesel oil with waste cooking oil (triglyceride), the results showed that the value of density was decreased from 916 kg m^{-3} to 877.5 kg m^{-3} after triglyceride was converted to be a biodiesel product.

Cloud point and pour point

Cloud point and pour point are important parameters for the use of liquid fuel at low temperature, especially in the winter countries [5, 21]. The data in Table 1 revealed that both the cloud point and pour point were within the recommended standards of biodiesel product which the cloud point and pour point were of 10 °C and 7 °C, respectively. Biodiesel oil from waste cooking oil is generally known that it has a high cloud point and pour point due to it was used to fry meal (e.g. meat, french fries, and omelet) which the fat from these sources might be mixed with the frying oil. Animal fat is commonly known to be a saturation fatty acid composition. Nevertheless, the synthesized biodiesel product displayed the cloud point and pour point within the range of biodiesel standard which could be very well employed against in a single-cylinder diesel engine especially in Thailand that is the tropical countries.

Oxidation stability

Oxidation stability of biodiesel was evaluated by the Rancimat method (EN 14112) with a stream of air as 10 Lh^{-1} at 110°C into the vessel containing the biodiesel sample [8]. The oxidative stability specifications of biodiesel meant the tolerance with reacted of air and moisture. In this case, there was directly involved in the acid-forming of biodiesel oil and this data would be applied to consider the storage of biodiesel product. The requirement of the oxidative stability following the European standard (EN14214) was more than 6 h [18, 19]. This result found that the biodiesel oil synthesized from waste cooking oil has a qualification of the oxidative stability to meet within the standard which was the value higher than 15 h.

Total acid number

The total acid number of biodiesel product has a direct effect on the wearing down and engine corrosion. The limitation of the total acid number of biodiesel agreeable with both European standard (EN14214) and American Society for Testing and Material (ASTM D6751) was to be less than 0.5 mg KOH per gram of oil [17, 18]. The total acid number of biodiesel product in this study was found to be acceptable with the standard specification of bio-auto liquid fuel. The data (Table 1) revealed that the total acid number was 0.26 mg KOH per gram of biodiesel oil which less than the requirement of the standard about one-half.

Heating value

The heating value of biodiesel fuel is the thermal energy when the fuel is burned completely and it can be evaluated by a bomb calorimeter. The heating value is an important property for defining the energy content of the biodiesel product which implicated the efficiency of fuels and physicochemical properties of the oil [22]. This research studied the heating value of the obtained biodiesel from waste cooking oil compared with biodiesel product derived from palm oil, lard oil, rubber seed oil, and petroleum diesel oil. All of the results indicate that biodiesel oil obtained from waste cooking oil was nearly equal with biodiesel product derived from palm oil, lard oil, and rubber seed oil. This case can be described that all of the feedstock for biodiesel production is a triglyceride compound and it has the same chemical structure but there is the difference in the part of long change hydrocarbon. When comparison the heating value of biodiesel fuel versus petroleum diesel oil, this study found that petroleum diesel oil showed the heating value higher than biodiesel product. However, only considering the heating value of fuel cannot evaluate the efficiency of the oil but need to consider various factors such as economically, environmental effect and utilization of feedstock that has in locally for biodiesel production. Thereby, biodiesel product derived from waste cooking oil can use directly to substitute petroleum diesel because they have a closely heating value.

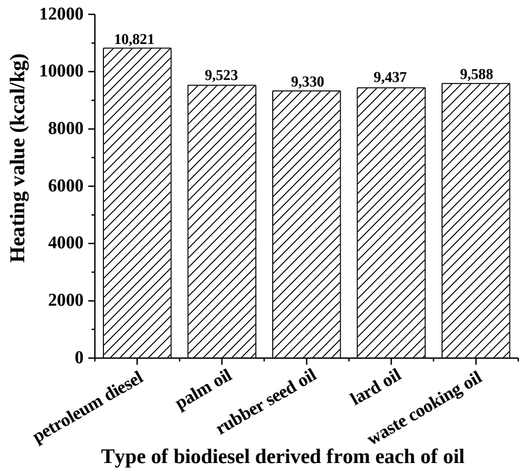
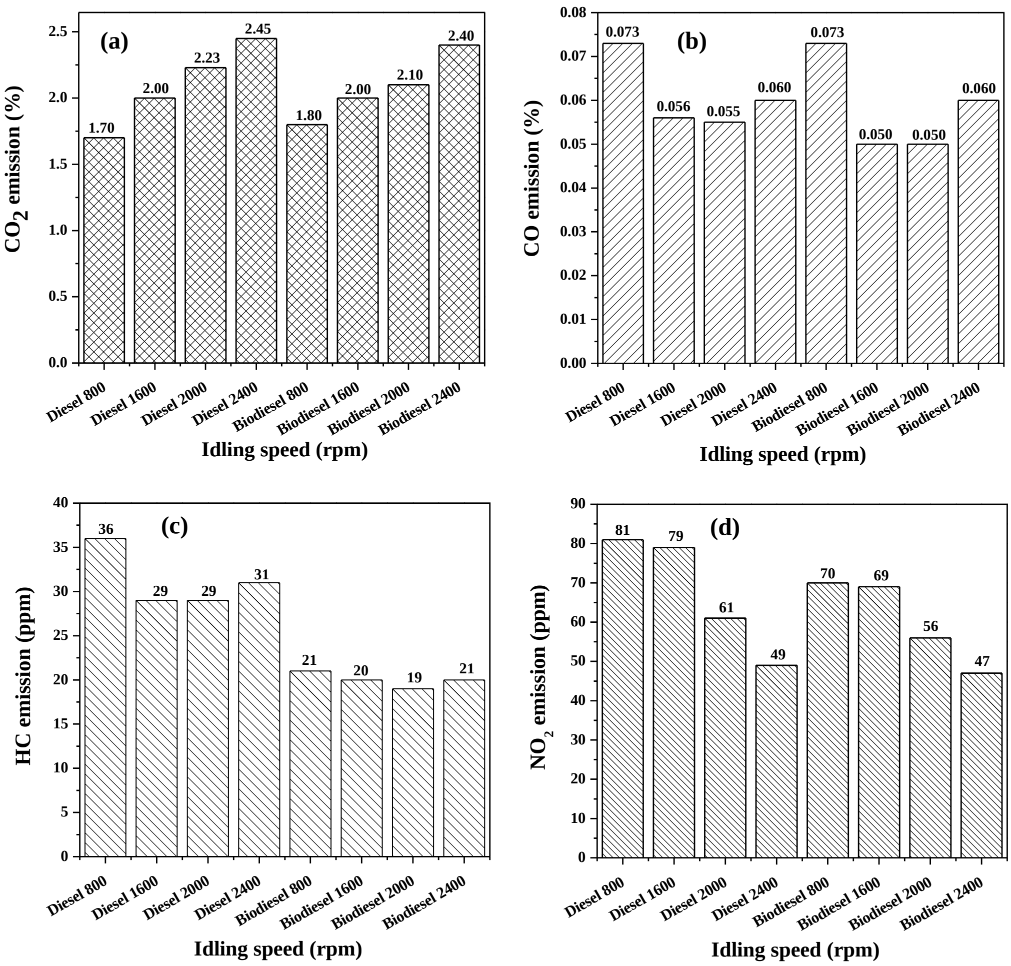


Fig. 4 the heating values of the obtained biodiesel from waste cooking oil compared with biodiesel product derived from palm oil, lard oil, rubber seed oil, and petroleum diesel oil.

The engine test by comparison diesel oil with biodiesel oil

The testing of diesel engine gases emission

A Flue Gas Analyzer EMS Model 5003 instrument was employed to measure exhaust gases emission when the engine combustion of fuel. For this research, the exhaust gases emission namely CO_2, CO, HC, and NO_2 were selected to test during the engine working. As shown in Fig. 5, the results indicated that the obtained biodiesel fuel has all of a trend exhaust gases emission less than the petroleum diesel oil. These results can be described that petroleum diesel oil lack of oxygen atom in the chemical structure but biodiesel oil found the oxygen atom as one of the compositions of the structures [2, 23, 24]. The oxygen that presence in the molecule structure of the fuel is one of the main factors to supplement combustions in the engine. Hence, this parameter could be concluded that the combustion of biodiesel product quite completely and this case directly affected the amount of exhaust gases emission of the engine. These result similarly agreed with the reports of Killol, A. et al., 2019 [23], Pillay, A.E. et al., 2012 [24], Lin, C.Y. and Lin, H.A. 2015 [25], and Patil, R.A. et al., 2018 [26].



Performance testing of engines

In this study, the experiment was engine performance on a single cylinder and four-stroke of Kubota RT100 which was agricultural diesel engines that normally used in Thailand. The engine speeds tested was ranging from 1,800 to 2000 rpm both the use of petroleum diesel oil and biodiesel oil as a fuel. The results showed that the engine torque and power obtained of biodiesel oil has nearby with diesel oil as presented in Table 2. Focus on engine torque, this experiment displayed at the engine speed 1800 to 1900 rpm, both of biodiesel oil and diesel oil have a maximum value of engine torque. However, brake specific fuel consumption of biodiesel fuel was greater than the diesel fuel due to the heating value of biodiesel oil lower than conventional diesel and including in the chemical structure of biodiesel has an oxygen atom led to the complete ignition of biodiesel. Furthermore, the density of biodiesel oil has valuable higher than diesel oil. This case engendered the injection of biodiesel oil into the engine higher than diesel oil [7, 11, 12, 23].

Table 2 the variation testing the performance of engines by using biodiesel oil compared with diesel oil.

Fuel	engine speed (rpm)	Engine Torque (Nm)[a]	Brake specific fuel consumption (BSFC) (g kWh^{-1})	Brake Thermal Efficiency (%)
Diesel oil	1800	35	13.75	56.73
	1900	32	14.24	54.75
	2000	30	14.43	54.03
Biodiesel oil	1800	28	17.18	52.73
	1900	24	20.27	47.71
	2000	23	21.65	41.85

[a] Tested 3 times

In addition, this work has also tested the use of biodiesel oil with real agricultural diesel engines by plowing to prepare the soil for cultivation in the rural area of Sakon Nakhon province, Thailand. The result indicated that the efficiency of biodiesel did not difference with diesel oil and engine breakdown was not observed because of biodiesel oil has a lubricant property. Therefore, biodiesel oil produced from waste cooking oil can be used with high efficiency for the real application especially the agricultural diesel engines which were small diesel engines

Conclusion

In this investigation, waste cooking oil was used as raw material for biodiesel production with a prototype solar reactor and the obtained biodiesel product was tested all of the physicochemical properties, the testing of diesel engine gases emission, and performance testing of engines. The obtained biodiesel properties were within both the EN14214 and ASTM D6751for the requirements standard of bio–auto fuels. The testing of diesel engine gases emission of biodiesel product found that exhaust gases emission has a trend lower than petroleum diesel oil. This is the advantage of biodiesel oil that overcomes diesel oil. The performance testing of engines compared between biodiesel oil against conventional diesel, the results indicated that the performance of biodiesel oil was similarly with diesel oil and no engine breakdown was observed. Hence, all of the results of this research work could conclude that biodiesel oil produced from waste cooking oil by using a prototype solar reactor was suitable and possible for the real application in the small diesel engine.

Acknowledgements

The authors would like to greatly appreciate to "Capacity Building and Supporting System for Researchers for Community and Social Development under the project; Biodiesel production from waste cooking oil using solar reactor : A case study of waste cooking oil bank of Matthayomwaritchaphum project, Waritchaphum District, Sakon Nakhon Province (RDG5940004-2S02)" for financial support. We are also thankful to [1]Program of Chemistry, Faculty of Science and Technology and [2]Biomass Energy Research Laboratory under Center of Excellence on Alternative Energy and Research and Development Institute, Sakon Nakhon Rajabhat University-Thailand for providing the equipment and tools for experimentation. Finally, the authors would like to thank Vidyasirimedhi Institute of Science and Technology-Thailand, for testing the obtained biodiesel with ^{1}H-NMR spectroscopy and Materials for Energy Research Group, National Metal and Materials Technology Center (MTEC), the National Science and Technology Development Agency-Thailand (NSTDA), for testing properties of biodiesel product.

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