Distilled Waste Plastic Oil as Fuel for a Diesel Engine: Fuel Production, Combustion Characteristics, and Exhaust Gas Emissions
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ABSTRACT: Waste plastic oil (WPO) derived from pyrolysis of plastic debris and municipal waste is one of the promising alternative fuels because of its similar carbon chain characteristics and physical properties to diesel fuel. WPO also contains naphtha which is gasoline-like and may not be well-suited to a diesel engine. Technically, naphtha should be eliminated from WPO by distillation, and the resulting product is called distilled waste plastic oil (WPOD). This work experimentally investigates the influences of these fuels burned in a diesel engine on combustion characteristics and exhaust gas emissions. Both WPO and WPOD fuels contribute to the larger amount of nitrogen oxides than diesel fuel. Carbon-based emissions increase when the engine operates with these pyrolysis fuels by retarding the ignition onset of their combustion occurrences. Meanwhile, their shorter-carbon-chain links provide a lower smoke index. However, brake thermal efficiency and brake specific fuel consumption are beneficial because of their high calorific value and cetane index.

INTRODUCTION

Fossil diesel fuel has been conventionally used as a primary source to fuel diesel engines and other burners in external combustion engines for over a century. Transportation, agriculture, and industry are sectors that use this kind of fossil fuel. With a limited amount of natural fossil fuel resources, scientists and engineers have given more attention to seeking for alternative fuels that are readily available and viable in practical use. They do not require a long period of time to decompose into various organic compounds to become ready as automotive or industrial fuels.

An alternative fuel of interest is waste plastic oil (WPO), which is produced from municipal solid waste (MSW) such as trash or garbage that is difficult to dispose of. Garbage amounts are mostly increasing year-by-year especially in developing and industrialized countries. Although some governments have issued campaigns and encouraged their people to recycle and reuse following the main waste management strategy, the amount of MSW is still too high. Several types and forms of plastics are the main component of the MSW. Separation of plastic waste from MSW can provide a large useful source of an alternative fuel like WPO. These plastic wastes can be converted into fuel by several processes (e.g., gasification, hydrocracking, catalytic cracking, and pyrolysis).

The most interesting process to transform the plastic waste is pyrolysis because it can produce tiny molecules of plastic waste with less hazard to the environment. In addition, the product from the pyrolysis process or the WPO contains 70% carbon chains similar to the diesel fuel with C10–C25 carbon chain, low viscosity, and specific gravity. However, according to previous research, there are some cases where the basic fuel properties of crude waste plastic oil were close to commercial gasoline and kerosene. Essentially, the chemical compositions of liquid fuel from the pyrolysis process are affected by different types of plastic waste. The research established by Istoto et al. showed that the chemical compositions of liquid fuel from high-density polyethylene (HDPE) and low-density polyethylene (LDPE) were analyzed by gas chromatography—mass spectrometry (GC-MS). The results indicate that composition of liquid fuel were naphtha, gasoline, and residues that can be used for WPO as an alternative fuel in spark ignition engines. The experimental results also found that increasing WPO concentration in the blend increased brake...
thermal efficiency and reduced brake specific fuel consumption. After combustion in a piston petrol engine in specified conditions, total unburned hydrocarbon (HC) emissions were reduced, and nitrogen oxide (NOX) emissions were increased. In the same experiment, the petrol engine can operate with waste plastics’ oil blends up to 20% without any modification of the engine.10

Numerous published research works specified that the WPO are practically similar in fuel properties to commercial diesel fuel.11,12 By this means, the tendency of applying WPO into a compression ignition diesel engine is practically viable. The effects of WPO utilization as alternative fuels in compression ignition engines were investigated and published in complete terms of prototype and management of waste plastic municipal solid for fully integrated waste plastic oil production.13 WPO tended to create more gaseous emissions such as carbon monoxide (CO), NOX, and HC than the commercial diesel fuel along with the increase in brake specific fuel consumption and the reduction of brake thermal efficiency.12,13 Moreover, some previous studies have already conducted the experiment of using the WPO that has undergone purification by distillation process. The consequences suggest that the use of distilled WPO (namely WPOD) as the blends with diesel fuel can improve the engine performance and emissions. It was observed that 50% distilled plastic pyrolysis oil blend exhibited a significant improvement in brake power and brake thermal efficiency along with the reduction in brake specific fuel consumption.14

Therefore, this study aims to disclose the comparison between waste plastic oil (WPO) and the distilled waste plastic oil (WPOD) produced from mixed plastic wastes with the benchmarks of conventional diesel fuel. The findings will provide information about physical and chemical properties, combustion characteristics, regulated emissions, and engine performance.

**MATERIALS AND METHODS**

**Test Fuels.** The pyrolysis plant for plastic oil production used in this study is shown in Figure 1. It is a slow pyrolysis process with a maximum feeding raw material of 5 tons/day. Waste plastic derived after MSW separation was prepared into aggregates (0.1–0.5 cm) using an agglomerator. The raw material was then conveyed to the pyrolysis chamber (2.5 m in diameter and 3.5 m in height) using a screw extruder, which was capable of preventing external air. The extruder was equipped with an electric heater to primarily heat up raw material, which enabled it to melt and evaporate in the chamber. The pyrolysis chamber was heated using a gas burner and maintained at temperatures between 350 and 400 °C. A stirrer was also installed on the top of the chamber to enhance heat transfer to the material. The waste plastic was converted into char and gas. The char was periodically removed from the chamber via a screw ash remover and stored in an ash chamber to cool down prior to its disposal. The gas was passed into a rectification tower to separate light and heavy vapor components. The heavy component was condensed and flowed back into the pyrolysis chamber while the light vapor moved upward inside the column and exited to the condenser, obtaining a liquid mixture of oil and water. The oil and water was then separated in the water/oil separator, employing the difference in liquid density. At a predetermined level, the oil overflowed to a holding tank prior to pumping it to an oil storage tank. The water was periodically removed from the water/oil separator to a wastewater tank, which was later treated before discharge. Finally, the resulting WPO was filtered to 1 μm to ensure that no deposits will be passed to the engine line system. To improve the quality of waste plastic oil and control chemical compositions present in the oil, an oil distillation system was employed by using a vacuum separation tower (50 mmbar abs) to separate the mixtures into the form of individual elements (fractions). The column size is 490 mm in diameter with 9000 mm height. The packing type is a pall ring (12.7 × 12.7 mm) with a packing height of 6000 mm. The heavy, middle, and light fractions were obtained from the bottom, center and top of the distillation tower with actual measured cut temperatures of 360, 282, and 176 °C, respectively. The bottom and top fractions contain carbon in the ranges of heavy oil and naphtha, respectively, while the middle fraction contains carbon content in the range of diesel fuel, as called WPOD. The derived WPO contains approximately 60% content similar to diesel fuel, while the others are naphtha and heavy oil occupying approximately 30% and 10%, respectively. These information are given in comparison to WPOD, in which naphtha was already removed from the waste plastic oil. Finally, the commercial diesel fuel complying with the regulation of the Department of Energy Business, Ministry of Energy, Thailand, was used as the reference fuel. This commercial diesel fuel contains 7% biodiesel by volume.

The ultimate analysis was used to determine the molecular compounds of the WPO fuel, including carbon (C), hydrogen (H), nitrogen (N), sulfur (S) and oxygen (O) using a CHNS
elemental analyzer; the results of the ultimate analysis of WPO are shown in Table 1. It can be observed that WPO provides C and H content of 87.103% and 12.956%, respectively, which plays a significant role in the combustion of fuels.\textsuperscript{15} Meanwhile, the oxygen content of WPO was found to be 0.603%; this exhibits an ability to improve combustion efficiency.\textsuperscript{16}

The distillation characteristics were important in terms of fuel properties affecting characteristics of combustion and emissions of engines. The WPO, WPOD, diesel, and naphtha were tested in accordance with ASTM D86 standard method. The obtained distillation curves of the test fuels are shown in Figure 2. It can be seen that the WPO and WPOD distillation curves were similar to the diesel fuel curve. The distillation temperature of WPO, WPOD, and diesel were in the ranges of 94–342 °C, 143.6–391.6 °C, and 190–352 °C, respectively. Moreover, the recovery amounts of 10% WPO and WPOD are due to lower temperatures compared with diesel fuel. Additionally, the 10% recovery for WPO was shown to be close to that of naphtha. Meanwhile, the final boiling points (FBP) of WPO and WPOD were higher in comparison with diesel fuel. The WPO distillation curve shows the highest deviation from the WPO distillation curve and exceeds the acceptable standard limit suggested. However, this result also showed that the distillation characteristics of WPO and WPOD can be used to consider alternative fuels for compression ignition engines. The observed naphtha was also obtained in the boiling temperature range of gasoline. The results of WPO and WPOD obtained from fractional distillation are numerated in Table 2.

Chemical characterization of the test fuels has been accomplished using gas chromatography–mass spectrometry (GC–MS). The GC-MS equipped DB-wax capillary section was employed by which 1 μL fuel sample was injected to the capillary length of 60 m, inside breadth of 0.25 mm, and film thickness of 0.25 μm. The working conditions were set up; inert helium gas was used to carry samples at a consistent stream rate of 1.0 mL/min. The GC furnace operated in the temperature setting mode from 70 to 250 °C. The temperature was first set to 70 °C and held for 3 min, and then the temperature was increased at the rate of 3 °C/min to 180 °C. Afterward, the temperature was increased by the rate of 10 °C/min to a final temperature of 250 °C and then held for 25 min. The entrance temperature was kept at 250 °C with a split proportion of 20:1. The infusion volume was 1 μL per test. The mass spectra identifiers were examined from mass to charge proportion varying from 35 to 550 m/z for a 250 °C source.\textsuperscript{17} The GC–MS results of test fuels are represented in Figure 3.

Waste plastic oil contains varying hydrocarbon content, separated by heavy and light parts, from the minimum to maximum carbon atoms that can be categorized into three types. First, the C4–C11 type represents a light part or gasoline where conventional gasoline is composed of hydrocarbons from five to nine carbon atoms. Second, the middle part or diesel is composed of hydrogen bonds between carbon atoms C12–C20. For last type, there is a high percentage of carbon atoms C20 and over.\textsuperscript{18} Figure 4 presents the results of the investigation on potentiality of waste plastic oil and the main substitute of diesel fuel. The results show that the quantitative trends of waste plastic oil and diesel fuel are similar. The WPOD has a higher percentage of C12–C20 than diesel fuel and WPO. Besides, the WPOD reduces the carbon atom percentage for the large carbon part (>C20) compared with WPO because distillation can help remove the heavy part. In addition, the carbon atoms C4–C11 proportion of WPOD was lower compared with WPO because this part was a condensed gas which can cause loss.

Properties of the Test Fuels. The properties of the test fuels are shown in Table 2. All fuel properties in the table were measured according to ASTM standards whose test methods are compliant with the regulation of Department of Energy Business, Ministry of Energy, Thailand. The limitation of chemical and physical properties of diesel fuel specified accordingly with the nation regulation (revised in June, 2020) is also revealed in Table 2. It can be observed that both WPO and WPOD fuels have physical properties resembling the diesel fuel range, especially the gross calorific values which are insignificantly different yet provide a high cetane index. By these properties founded, the two fuels are promising to be used as a primary fuel in the compression ignition engine similar to the diesel fuel.

Experimental Setup and Procedure. The experimental investigation was conducted on the four-cylinder direct injection diesel engine with a naturally aspirated and water-cooled system. The engine was operated at 2500 rpm as a usual operating speed with different torque loading conditions: 30, 50, 70, 90, and 110 N m. The engine loads were applied and measured by using a hydraulic dynamometer. All the data were logged after the engine operates constantly. The intake air flow rate, humidity, engine oil pressure, intake air temperature, and the exhaust gas temperature are attained from the standard engine test rig. The in-cylinder pressure is required to study on the pressure trace and combustion characteristics. A Kistler 6052C pressure transducer was installed to observe the trace. The pressure trace is amplified by using a Kistler 5064C charge amplifier before sending data to the data acquisition board. Also, the engine crank position is necessary as the datum point of the measured in-cylinder pressure, which was provided by

| Table 1. Chemical Compositions of Waste Plastic Oil | chemical compositions | wt % | C | H | O | N | S |
|---------------------------------------------------|-----------------------|------|---|---|---|---|---|
| ultimate analysis                                  |                       |      | 87.103 | 12.956 | 0.603 | - | - |

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using Kistler crank angle encoder set, type 2614CK1. The schematic diagram of the experimental setup used in the study is depicted in Figure 5, and the technical specifications of the diesel engine are given in Table 3. To determine the gaseous emission, data were obtained by a Testo 350 gas analyzer for NOX, HC, and CO. Meanwhile, a Testo 308 smoke tester was used to analyze the smoke emission. The specification of emission analyzers are shown in Table 4.

## RESULTS AND DISCUSSION

The experimental results are analyzed and discussed into three parts as follows: (1) engine performance focusing on the brake specific fuel consumption and brake thermal efficiency; (2) combustion characteristics with respect to in-cylinder pressure, rate of heat release, and coefficient of variation in indicated mean effective pressure; and (3) gaseous emissions such as NOX, CO, HC, and smoke opacity. In each section, the comparison between results from WPO and WPOD fuels were used to analyze the smoke emission. The specification of emission analyzers are shown in Table 4.

### Engine Performance Characteristics

Brake specific fuel consumption (BSFC) represents the ratio of engine fuel rate and brake engine power. BSFC is usually affected by fuel properties such as caloric value, viscosity, and density.\(^{19}\) Figure 6 shows the BSFC variation of using WPO and WPOD fuels at different engine load. The result showed that BSFC decreased with increasing engine load for all tested fuels. As compared with diesel fuel, BSFC was higher with WPO fuel operation compared with diesel fuel operations at low and middle engine loads. Moreover, BSFC is slightly decreasing by using WPOD fuel when compared with WPO fuel. The calorific value of WPO fuel is less than diesel fuel. Because of these reasons, the BSFC for WPO was higher than that of diesel.\(^{20}\)

Brake thermal efficiency (BTE) is used as the criteria to discuss the engine performance from using WPO and WPOD fuels. The higher thermal efficiency shows the higher capability of the engine to produce work over the amount of energy input.\(^{21}\) Brake thermal efficiency results of using WPO and WPOD fuels are depicted in Figure 7. The change in BTE of WPOD fuel is increased from the diesel fuel reference in most loading conditions. The WPO fuel resulted in less heat was being converted into work and provides lower efficiency; (2) combustion characteristics; (3) gaseous emissions such as NOX, CO, HC, and smoke opacity. In each section, the comparison between results from WPO and WPOD fuels were taken by using commercial diesel fuel as the reference.  

### Combustion Characteristics

When the engine fired, the in-cylinder pressure trace was measured with respect to the engine crank angle and recorded for 120 consecutive engine cycles. This data can be used to interpret the combustion characteristics in the aspect of rate of heat release (RoHR) by using eq 1 derived from the first law of thermodynamics.\(^{23}\)
\[
\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta}
\]

where \(dQ/d\theta\) is rate of heat release (J/deg), \(p\) is in-cylinder pressure (Pa), \(V\) is combustion chamber volume (m\(^3\)), and \(\theta\) is crank angle. The constant specific heat ratio (\(\gamma\)) calculated by the polytropic process \((pV^\gamma = \text{constant in the expansion stroke where the heat is released})\). \(^22\)

Figure 8 depicts the rate of heat release and the in-cylinder pressure trace from WPO combustion compared with the
diesel fuel combustion at the load of 30 N m. It can be observed that WPOD fuel starts burning earlier than the diesel fuel with the slightly higher peak of the rate of heat release and the in-cylinder pressure. On the contrary, WPO fuel seems to provide the most inhibition of the start of combustion. This pattern continues to present when the engine increases to the higher load ranges of 50, 70, and 90 N m, as shown in Figures 9–11. It can also be observed that all of the traces are getting closer and becoming similar to the reference diesel traces. Eventually, diesel fuel becomes the predecessor among all the fuel in the high load of the 110 N m condition as shown in Figure 12.

Both WPO and WPOD fuels have physical properties very close to the diesel fuel except for the cetane index. It is clearly shown in Table 2 that WPO and WPOD fuels are higher for the cetane index, which indicates the ease of combustion onset. This implies that shorter in ignition delay period than the diesel fuel can be observed. However, this can be used to explain only traces of the WPOD fuel, while the combustion characteristics of WPO fuel show the opposite tendency, which has to be explained by bulk modulus. Since WPO fuel has the lowest density among these three fuels, it is prone to the lower bulk modulus. The low bulk modulus allows the substance, WPO fuel for this case, to be more compressed before the fuel leaving the nozzle.23 With the same injection timing, WPO was
gathered in an amount and may have used the longer period before ignition because of some particular heterogeneous charge from the gathered WPO fuel. Also, WPO fuel contains some part of naphtha as it was claimed that it has the longer ignition delay than the diesel fuel.24 In some cases, the slightly delaying of the start of combustion allows more available time for mixing the fuel with the air charge to be more homogeneous.25 However, for this case, the ignition may delay and occur after the piston traveled past the top dead center of the engine, yielding the lower in-cylinder pressure peak and the worse emission result. This phenomenon is less effective at higher load, corresponding to the higher combustion temperature generated in each cycle. The patterns of the WPO have become closer to the reference diesel fuel and show the sign of reduction in emissions, which will be further discussed in following section.

The coefficient of variation in indicated mean effective pressure (COVIMEP) is an important engine factor which indicates the combustion stability of the engine operation. Generally, it is accepted that COVIMEP < 10% is the upper limit of stable combustion.26 The COVIMEP values of the test fuels at different engine loads are represented in Figure 13. It can be seen that the COVIMEP decreased as the engine operating loads increased for all fuels. This is due to the increase of the fuel extent in the mixture.27 The COVIMEP of WPO and WPOD fuels remains under 10% for all engine loads. However, the use of WPO and WPOD fuels resulted in higher COVIMEP when compared with diesel fuel for all engine loads. A higher COVIMEP values indicate a lesser stability in engine operation. When comparing between WPO and WPOD fuels, WPOD has significantly lower COVIMEP compared with the WPO.

**Emission Characteristics.** This section will discuss about the level of gaseous emission: NOX, CO, HC, and smoke opacity. Comparatively with diesel fuel, NOX and CO were increased from using either WPO or WPOD, while the amount of HC from WPOD was decreased from the baseline. Both WPO and WPOD fuels reduce the amount of smoke emission. NOX emission is one of the main pollutants from the combustion of diesel engine due to the diesel engine generally burns with the excess amount of air. Figure 14 shows the NOX emission concentrations by using WPO, WPOD, and diesel fuels. Significantly, using both fuels increases the amount of NOX emissions. Besides the availability of N2 in the air charge that affects the formation of NOX, the large amount of heat energy at high temperature is also required to dissociate N2 atoms to be radical atoms for the formation.28 It can imply that the higher amount of NOX emission indicates the higher heat provided from the combustion. NOX was drastically increased.
when using WPOD fuel while WPO fuel slightly increased NOX emission levels. WPOD has a similar calori-

fic value to the diesel fuel but a higher cetane index. It appears that the more advanced starting of the combustion provides the highest peak of the in-cylinder pressure at the top dead center. More heat is generated through the longer available time to complete the combustion, and it leads to higher NOX emission. In contrast, less NOX was emitted through the worse and more inhibited combustion by using WPO fuel. The difference in the amount of NOX emission is shown to become smaller in the higher load range, where a greater amount of fuel was injected to the combustion chamber. The richer combustible charge of WPOD fuel becomes more difficult to ignite, which is supported by the in-cylinder pressure traces, and leads to less available time for NOX formation. In the case of WPO fuel, the residual in-cylinder temperature from the combustion influences the ignition to become more advanced. Therefore, the patterns of the combustion become close to each other and provide a similar period of time for the formation of NOX.

The level of CO emission is depicted in Figure 15. It can be observed that using WPO fuel dramatically increases CO emission in the low load and exhibits very small difference from diesel fuel in the higher load region. WPO fuel starts the combustion retarder than that of both diesel and WPOD fuels in the low load. The retarded combustion allows the shorter period of the oxidation time. CO2 emission which is the product of the complete combustion cannot be achieved within this period. Also, the homogeneity of the combustible charge is responsible for the high amount of CO emission. Since WPO fuel may leave the nozzle later than the physical injection timing due to its bulk modulus, it may, therefore, have insufficient time to vaporize and mix with the charge homogeneously. Moreover, some particular rich areas of the mixture have not been completely combusted, resulting in CO formation. Increasing the load provides the combustion to be more expedient and more completed through the higher temperature inside the cylinder. By this high load condition, more heat was available for CO2 oxidation. WPOD fuel shows the lower amount of CO through its better combustion. This can be referred to the NOX from WPOD combustion that was emitted to be higher than WPO.

Among other possible sources, HC emission is also derived from the incomplete combustion; the levels of HC emitted are as shown in Figure 16. The same trends are observed as the CO emissions; WPO generally provide higher HC emission than WPOD fuel and its difference is smaller when increasing the engine load due to a greater extent of thermal reaction. Apart from the lack of homogeneity of the charge, the heat transfer between combusted gas and the cylinder wall also play a role. Although the low thermal reaction occurred in the low load, there was still some heat loss transfer through the in-cylinder environment to the engine cylinder wall. This heat loss may reduce the temperature inside the combustion chamber and cause flame quenching early before hydrocarbon can be burnt. The effect of the heat transfer in the higher load was weakened since the high load combustion provides more thermal reaction, which can help to maintain in-cylinder temperature. HC emission can be effectively burnt when using WPOD fuel. The level was shown to be even slightly lower than diesel fuel reference. Its advanced starting of the combustion allows longer time for the fuel hydrocarbon to be combusted.

The level of smoke is generally varied with respect to the amount of carbon atoms of the fuels. The higher level of smoke results in incompleteness of the combustion. Figure 17 shows the result of smoke index from using WPO and WPOD fuels.
By using these fuels, the smoke index was lower than that of the conventional diesel fuel. WPO fuel provides a lesser smoke index. Moreover, smoke index also decreases with respect to the higher engine load. Since the amount of carbon atoms and amount of fuel injected plays a key role for the smoke level, the kinds of chemical group such as aromatics are also responsible for the formation of smoke. Both pyrolysis fuels have fewer aromatic groups than conventional diesel fuel, which can explain the decrease of smoke index that is due to fewer available compounds for soot particle growth and particle formation in this experiment. Moreover, WPO fuel which contains some part of naphtha also has the shorter carbon chain length. It leads to the lower amount of leftover solid particles in the smoke and also provides a similar result to the other work. Additionally, the better combustion in the higher load burns more soot and causes the lower smoke index.

CONCLUSIONS

The pyrolyzed fuels such as WPO and WPOD from municipal waste have similar physical properties with the conventional diesel fuel. Both pyrolyzed fuels show good tendencies to be utilized with diesel engine through the experimental results in this work. Greater brake thermal efficiency and lower brake specific fuel consumption can be achieved by the high calorific value and cetane index of this pyrolyzed fuel. Smoke index also decreases when using WPO and WPOD fueling because of their lesser aromatic compounds. On the other hand, some of their drawbacks were shown in terms of emission. The gaseous carbon-contained emissions are evidently present in the low load condition as well as the increase in NOx, which can be explained by the differences in combustion characteristics.

Therefore, the utilization of these waste pyrolysis fuels causes slightly different effects from the conventional diesel fuel, but some other aspects are required for further study. For example, the constituent of the fuel that is caused by the sources of the municipal waste needs to be further investigated. This area of study may lead to better fuel quality and improved physical properties. Also, the combustion controlling strategy may help in simultaneously improving exhaust emissions and efficiency.

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Notes

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