Fuel Properties, Performance and Emission of Alternative Fuel from Pyrolysis of Waste Plastics

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Abstract. Increase in energy demand, stringent emission norms and depletion of oil resources have led the researchers to find alternative fuels for internal combustion engines. Pyrolysis oil extracted from waste plastics, by pyrolysis, as a fuel for internal combustion engines has been demonstrated to be one of the best available waste management methods. This research aimed to study and compare fuel properties, engine performance and emission of alternative fuel from pyrolysis of waste plastics, which focused on physical and chemical properties of waste plastic crude oil (WPCO) and waste plastic oil (WPO) obtained by fractional distillation process. The result shows that the physical and chemical properties of WPCO are quite different from commerical diesel while the fuel properties of WPO were found to be similar to that of diesel. The experimental results showed that the use of WPO led to an increase in brake specific fuel consumption but the slightly reduction in the brake thermal efficiency was founded with respect to diesel fuel. The combustion of WPO tended to increase NOX while a reduction in smoke was obtained compared with the pure diesel fuel.

1. Introduction
Plastic waste is a big issue in Thailand, because the amount of recycled plastic remains low due to the high investment requirements for recycling and the high operating costs of recycling facilities [1]. Plastic waste is an ideal source of energy due to its high heating value and abundance. Therefore, in recent years, various plastic to fuel (PTF) or waste to fuel (WTE) technologies such as gasification, pyrolysis, refuse derived fuel (RDF), and plasma arc gasification have gained significant attention for the management of plastic waste. The most attractive technique for chemical feedstock recycling is pyrolysis. Pyrolysis is a decomposition process of long-chain hydrocarbon (polymer) molecules into smaller sizes (monomer) with the use of high heat (450-800 °C), in a shorter duration and a condition with the absence of oxygen, generating products in form of carbon, as residues and volatile hydrocarbons which can be condensate as fuel and non-condensable as gaseous fuel. In addition, researchers showed that the properties of the liquid fuel from waste plastics are practically like diesel fuel and the engine could be operated using neat pyrolysis oil from waste plastics. Experimental engine results from previous studies have been reported that pyrolysis oil exhibited higher brake thermal efficiency and higher regulated exhaust emissions such as nitrogen oxides, hydrocarbon, and carbon monoxide with respect to diesel combustion [2]. In this study, it is aimed to study the characterization and fuel properties of alternative fuel from pyrolysis of waste plastics, which focused on physical and chemical properties of the fuel and compare engine performance and emissions.
2. Methodology

2.1. Materials
The raw materials utilized in this study were derived from waste plastics such as plastic bag waste collected from scavengers around Suranaree Subdistrict, Nakhon Ratchasima, Thailand. The compositions of the plastics were categorized as polyethylene (PE), and polystyrene (PS) of which approximately 70% were organic contaminated contents.

2.2. Conversion process
Pyrolysis process is the chemical decomposition of organic substances by heating in the absence of oxygen. The waste plastics is gently cracked by adding catalyst and the gases are condensed in a series of condensers to give a low sulphur content distillate. All this happens continuously to convert the waste plastics into fuel. All the gases from this process are treated before it is let out in atmosphere. The flue gas is treated through scrubbers and water/chemical treatment for neutralization. The non-condensable gas goes through water before it is used for burning. Since the plastics waste is processed about 300-350 °C and there is no oxygen in the processing reactor, most of the toxics are burnt.

2.3. Experimental setup
The engine used for this study is a four-stroke, single-cylinder, water-cooled, direct injection compression ignition engine. An eddy current dynamometer with a load cell was used to load the engine. The tests were performed at rated speed of 1500 rpm and three different engine loads (25%, 50% and 75% of maximum engine torque). Commercial diesel fuel was used as a baseline comparison with WPO for the engine run tests. An air box was used to measure the air flow rate to the engine and volumetric fuel flow rate was measured using a burette and stopwatch. The TESTO 350 analyzer was employed to measure nitrogen oxide (NOX) and TESTO 308 was used to evaluate smoke index. At every load, readings were taken after the engine reached steady state. For every refueling, engine was kept running for 10 minutes such that it consumes entire fuel entangled in fuel pipe lines. Repeatability of readings was guaranteed by duplicating the investigations thrice. The technical specifications of the engine are given in Table 1.

| Engine | Specifications |
|--------|---------------|
| Model  | Kirloskar TV1 |
| Engine type | 1 cylinder, 4 strokes, Water cooled, Direct injection |
| Bore x Stroke | 87.5 x 110 mm |
| Swept volume | 661 cc |
| Rate output | 3.5 kW at 1500 rpm |
| Compression ratio | 12:1-18:1 |
| Dynamometer | Eddy current |

3. Results

3.1. Chemical characterization
The pyrolysis oil or waste plastic crude oil (WPCO) and waste plastic oil (WPO) obtained by the fractional distillation used in this study is extracted from waste plastic. Gas chromatography mass spectrometry (GC-MS) was used to analyze the chemical compounds present in the WPCO compared with WPO. The GC-MS results of WPCO and WPO were presented in Figure 1. The major chemical compounds present in WPCO and WPO and their percentage area were listed in Table 2.
Figure 1. Total ion current chromatogram for WPCO and WPO.

Table 2. Principle constituents (area %) identified by GC-MS

| Carbon content | WPCO | WPO   |
|----------------|------|-------|
| C4             | 2.77 | Not detected |
| C5             | 0.84 | Not detected |
| C6             | 3.76 | Not detected |
| C7             | 5.38 | Not detected |
| C8             | 34.02 | 1.03 |
| C9             | 19.94 | 0.73 |
| C10            | 28.49 | 2.28 |
| C11            | 0.53 | 5.71 |
| C12            | 0.75 | 9.78 |
| C13            | Not detected | 10.08 |
| C14            | Not detected | 11.03 |
| C15            | 0.67 | 10.48 |
| C16            | 0.19 | 8.71 |
| C17            | 0.26 | 7.90 |
| C18            | 0.32 | 8.88 |
| C19            | 0.36 | 7.86 |
| C20            | 0.24 | 8.10 |
| C21            | 0.36 | 3.63 |
| C22            | 0.27 | 2.29 |
| C23            | 0.20 | 1.08 |
| C24            | 0.19 | 0.43 |
| C25            | 0.20 | Not detected |
| C26            | 0.18 | Not detected |
| C27            | Not detected | Not detected |
| C28            | 0.08 | Not detected |
The WPCO and WPO contain many hydrocarbon compounds both light and heavy fractions and from the lowest carbon atom number (C4-C5) to the highest one (> C20). It could be classified into 3 groups to easily identify. C4-C11 group represents light or gasoline fraction due to the tendency that the largest percentage of carbon atom number in the gasoline is commonly around C7, C8, and C9. C11-C20 group could represent medium and heavy fractions, including diesel fraction. The diesel fuel fraction mostly contains high percentage of the atom number C16-C20 [3]. The result of this study showed that waste plastics composition strongly influences propensity formation of certain hydrocarbons group. The WPCO of this study leads to form mostly C12-C20 fraction. While the fractional distillation led to the trend of similarity between WPO and diesel fuel. It can be seen that chemical compounds were found to be closer to diesel fuel.

3.2. Physical and chemical properties

The basic physical and chemical properties of WPCO, WPO and commercial diesel fuel as reference fuels were measured according to ASTM standards and were shown in Table 3. The experimental results showed that WPCO possessed lower kinematic viscosity, flash point, distillation temperature, and gross calorific value while density and specific gravity were higher with respect to those of WPO. However, the fuel characteristics of WPO such as density, viscosity, and gross calorific value have similar properties with those of fossil fuels. Therefore, WPCO can’t be used as alternative fuel for compression ignition engines due to the properties of WPCO were found to be closer to gasoline.

Table 3. Physical and chemical properties of test fuels.

| Fuel property                        | Method (ASTM) | Diesel | WPO  | CWPO  |
|--------------------------------------|---------------|--------|------|-------|
| Density at 15.6 °C (kg/m³)           | D1298         | 834    | 899  | 823   |
| Specific gravity at 15.6 °C           | D4052         | 0.835  | 0.900| 0.824 |
| Kinematic viscosity at 40 °C (cSt)   | D445          | 3.44   | 1.66 | 3.11  |
| Flash point (°C)                      | D93           | 66     | 35   | 54    |
| Distillation 90% vol. (°C)            | D86           | 348    | 164  | 276   |
| Calculate cetane index                | D976          | 56.57  | -    | 46.7  |
| Gross calorific value (MJ/kg)         | D240          | 45.56  | 37.72| 45.24 |

3.3. Engine performance

In present section, performance parameters such as brake specific fuel consumption (BTE) and brake thermal efficiency (BTE) of the engine according to operation load for all the test fuels are presented and analyzed. The results showed in the plots correspond to an average of three different measurements. The variations of BSFC and BTE as a function of engine load for test fuels are shown in Figure 2. It can be seen that the BSFC decreased as the engine operating loads increased for all fuels. The lower BSFC implies that less amount of fuel is needed to generate unit power output. WPO presented higher BSFC than commercial diesel fuel due to its lower calorific value that required more quantity of oil to be burnt to produce the same power output similar to commercial diesel fuel (see Table 3) [4]. BTE indicates the ability of combustion system to accept the experimental fuel and provides a comparable means of assessing how efficiently the fuel was converted into mechanical output [5]. WPO showed a drop-in efficiency, since more energy is spent to breakdown the heavy hydrocarbon chains (C13 to C22) [4]. Besides, higher BSFC was obtained from the combustion of waste plastic oil, resulted in the lower BTE with respect to commercial diesel fuel for all engine loads tested.
3.4. Emissions

The emissions emitted from the engine, measured at tail pipe corresponding to variation of load are measured. The results showed in the plots correspond to an average of three different measurements. The variation of the NOX emissions and smoke opacity with engine loads and test fuels was shown in Figure 3.

Oxides of nitrogen present in emissions is the combination of nitric oxide (NO) and nitrogen dioxide (NO2). In diesel engines the mechanism that produces the majority of NOX is the thermal mechanism due to availability of oxygen, reaction time and combustion temperature [6,7]. It can be seen that the NOX emissions for WPO operation is higher than that for commercial diesel fuel. The reason that NOX emissions is the higher nitrogen content in the fuel that promotes the NOX formation by fuel mechanism. The variation of smoke opacity is attributed to the high overall equivalence ratio and the number of fuel rich regions in the combustion chamber when the engine is operated at high load, resulting in the high critical conditions for soot formation which relates to the increase in smoke emissions [8]. The lower smoke emissions were found for the combustion of WPO compared to diesel fuel. The reason for reduced smoke for WPO can be early evaporation of fuel leading to premixed or homogeneous charge inside the cylinder [6].
4. Conclusion
Pyrolysis oil or waste plastic crude oil (WPCO) and waste plastic oil through the fractional distillation (WPO) were extracted from waste plastics by pyrolysis process and its chemical composition was characterized by using GC-MS. Later, this study sets out to investigate the effects of WPO in a single cylinder on engine performance of a DI diesel engine was then compared with commercial diesel fuel. The following conclusions were drawn from the investigation.

- The properties of WPCO were found to be closer to gasoline. GC-MS characterization revealed that WPCO consists of 22 chemical compounds with light hydrocarbon chains.
- The properties of WPO were found to be closer to commercial diesel fuel. GC-MS characterization revealed that WPO consists of 17 chemical compounds with heavy hydrocarbon chains.
- The physical and chemical properties of WPCO and WPO were analyzed and compared with commercial diesel fuel and found that it has properties difference to that of diesel fuel for WPCO. While fuel properties of WPO was found to be closer to commercial diesel fuel.
- The use of WPO tended to increase brake specific fuel consumption, resulting in the decrease in brake thermal efficiency when compared with commercial diesel fuel.
- The combustion of waste plastic oil tended to increase NOX while a reduction in smoke was obtained with respect to diesel fuel combustion.
- WPO has been shown a feasible alternative for used as fuel in compression ignition engines.

5. References
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