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# Utilization of waste polyethylene pyrolysis oil as partial substitute for diesel fuel in a DI diesel engine

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**Abstract**

This study aims to utilize pyrolysis oil produced from the pyrolysis of waste polyethylene in a direct injection (DI) diesel engine. In this paper, the performance and emission of a diesel engine have been studied using blends of waste polyethylene pyrolysis oil with diesel fuel under different loads condition. The waste polyethylene pyrolysis oil (WPO) used in this work was produced from the sequential pyrolysis and catalytic reforming of polyethylene bag after crushing and washing using natural zeolite (NZ) catalyst. Engine tests have been done using a four-cylinder and four-stroke diesel engine with the compression ratio of 22 and water cooling system. The experimental works were done at the rated engine speed of 1800 rpm. The results indicated that the brake thermal efficiencies are slightly higher as compared to that of diesel while the brake specific fuel consumption (BSFC) is slightly reduced when blending diesel fuel with WPO. Moreover, WPO-diesel fuel blends at various engine loads are also found to have influences on the emissions of CO, HC, NOx, and the smoke opacity. The NOx emission is found to be lowered by blending diesel with WPO. The decreased NOx emission is due to the decrease of the in-cylinder temperature by the effect of the non-homogeneity of WPO. The emissions of HC and CO of WPO-diesel blends are higher than that of diesel. Finally, the smoke opacity for WPO blends is slightly higher at higher loads.

*Keywords: Waste plastics, pyrolysis oil, diesel engine, performance, emission.*

## 1. Introduction

The global growth and wealth composition has changed drastically in the last three decades. Increasing the economic prominence of several countries such as China, India, Brazil, and Russia and the recent economic crisis in the Europe and United States contributed significantly for the changing balance of the global economic power. These changes will affect the economic situation in developing countries such as countries in the South East Asian Region (ASEAN). Nowadays, economic development in ASEAN countries is growing rapidly. Asian Development Bank Institute reported that ASEAN members have the ambition to triple the region's average real per-capita gross domestic product (GDP) from about $3,000 in 2010 to about $10,000 by 2030, [1]. As a result, ASEAN economic development led to an increase in energy consumption in all sectors of economic activities. As reported by ASEAN Energy Center, the total final energy consumption of ASEAN countries increased to 343 MTOE (million tonnes of oil equivalent) in 2005 growing at an average annual growth rate of 4.2 percent over the 1990 to 2005 period [2]. On the other hand, the energy reserves will decrease if there is no new sources of energy are found since it was dominated by petroleum-derived fuel.

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Several steps are being initiated around the world to find an alternative petroleum-based fuel due to the impact of the increase in the oil price and the depletion of petroleum reserves such as biodiesel [3,4,5,6] and oil from waste plastics. The use of biodiesel for blending with diesel fuel will change the physical properties of the fuel such as viscosity and density [7,8]. Therefore, some modification should be conducted to enhance the engine performance. Waste plastic pyrolysis oil which is produced from the pyrolysis of waste plastics, can be used as an alternative fuel for substituting petroleum-based fuel due to the abundant sources of waste plastics [9-11]. Diesel engines as one of the internal combustion engines which are widely used either in an automotive vehicle or in power plant have a high potential for employing plastic oil as a fuel. Among any regular internal or external combustion engines, diesel engines have the highest thermal efficiency due to their high compression ratio. However, diesel engine emits high levels of NOx and smoke which will have an impact on human health. Therefore, the strict emission regulation and the petroleum fuels depletion have necessitated the search for alternative fuels for diesel engines [11-13]. Dhinesh et al. has succesfully reduced the NOx emission by employing nano emulsion nerium oleander biofuel [5] and improved the soot formation by modifying the combustion bowl using shallow depth re-entrant and torroidal re-entrant combustion bowls [6].

The efforts to attain the reduction of the fuel consumption and the engine emissions while keeping the engine performance can be done based on the characteristics of injection. The most important characteristics of injection are the injection pressure, the injection timing and the injection duration. The injection process affects the harmful NOx and smoke emissions. During the intake process, diesel engines induct only air. Late in the compression process, fuel is directly injected into the combustion chamber and mixes with air which has been compressed to a high temperature. The high temperature of the air serves to ignite the fuel. The power output of the diesel is controlled by adjusting the fuel flow rate while the volumetric efficiency is roughly constant [14].

Utilization of plastic oil for fueling diesel engines is currently getting more attention. However, a very little study has been conducted to test this fuel in diesel engines. The performance and emission of plastic oil have been investigated in a direct injection (DI) diesel engine [15]. Ignition delay was longer by around 2.5 $^{o}$CA in the case of plastic oil compared to that of diesel. The thermal efficiency was found to be higher up to 75% of the rated power. The blending of plastic oil with diesel fuel has also been studied by some researchers [9,10,16]. The performance and emission of plastic oil in a diesel engine strongly depend on the chemical composition and the physical properties of the plastic oil.

Mani and Nagarajan [13] studied the influence of the injection timing on the performance and the emission characteristics of a DI diesel engine running on plastic oil. The result showed that by retarding injection timing, the brake thermal efficiency of the diesel engine was found to be higher. On the other hand, the emissions of CO, NOx, and unburned hydrocarbons were found to decrease. Retarding the injection timing leads to the fast start of combustion and continues in the power stroke [13]. The exhaust gas recirculation (EGR) has been introduced to reduce the NOx emission from diesel engines [17]. The NOx emission was found to be reduced due to the presence of higher heat capacity gases which reduces the peak combustion temperature.

However, most of the study discussed above have been done at the compression ratio of 17.5. Utilization of plastic oil at a higher compression ratio of diesel engines have not yet been studied. The ratio of compression is the main parameter during combustion of the fuel in a compression ignition engine. A higher compression ratio has effects on ignition timing, end temperature and pressure at the end of compression and has a similar effect as raising the inlet air temperature and boosting the intake pressure [18]. It also gives faster laminar flame speed and consequently reduces the ignition delay period [19]. Nagaraja et al. [20] studied the effect of the compression ratio in diesel engine running on preheated palm oil – diesel blends and showed that while increasing the compression ratio of the engine, the mechanical efficiency was increased at full load condition which leads to better thermal efficiency of the engine. Currently, a lot of diesel engine is running at high compression ratio. In this paper, we studied the performance and emission of a diesel engine by blending waste polyethylene pyrolysis oil with diesel fuel at a compression ratio of 22 of the diesel engine.

## 2. Materials and Methods

### *2.1. Materials*

The waste polyethylene pyrolysis oil (WPO) used in these experiments produced from the sequential pyrolysis and catalytic reforming of polyethylene bag after crushing and washing using natural zeolite (NZ) catalyst with the calcination treatment. In these experiments, about 2 kg of the feedstock was fed into the reactor of pyrolysis. The experiments were conducted at the pyrolyzer temperature of 450 ℃ and the reformer temperature of 450 ℃. The detailed procedure to produce WPO can be seen in the previous work published by the author [21-23]. The physical properties of WPO and diesel fuel are summarized in Table 1. WPO-diesel blends of 10% and 20% were used to run the engine. These blending ratios are denoted as 10% WPO and 20% WPO. The appearance of WPO-diesel blends is shown in Fig. 1.

Table 1. Physical properties of WPO and commercial diesel fuel

| Properties | Units | WPO | Diesel |
|---|---|---|---|
| Density | $g/cm^3$ | 0.868 | 0.845 |
| Kinematic viscosity | $mm^2/s$ | 2.191 | 4.012 |
| Flash point | ℃ | <10 | 66.5 |
| Pour point | ℃ | 24 | 6 |
| Water content | % vol | trace | trace |
| Heating value | MJ/kg | 45.58 | 45.79 |

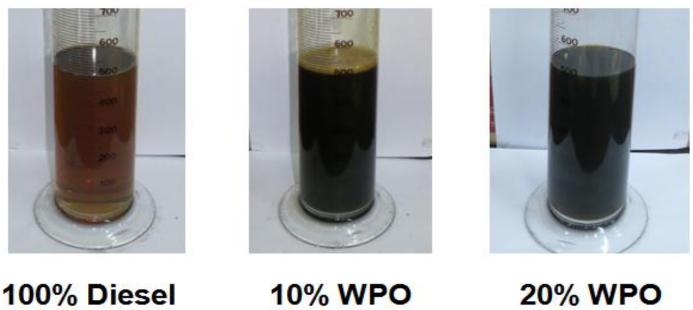


Fig. 1. Diesel fuel and WPO-diesel blends used in the experiments.

### *2.2. Experimental setup of diesel engine*

Engine tests have been done using a four-cylinder and four-stroke diesel engine with water cooling system. The engine type was Nissan Diesel SD22 Series with the compression ratio of 22. The snapshot of the diesel engine test bed can be seen in Fig. 2. The technical specifications of the test engine are given in Table 2. The engine was coupled to an eddy current dynamometer to give the engine load. The air consumption of the engine was measured by using a U-tube manometer. The flow rate of fuel was measured on the volumetric basis by using a burrete and a stopwatch. A thermocouple connected to a digital temperature indicator was used to measure the exhaust gas temperature. The exhaust emissions were measured by using Star Gas and Optima 7 analyzers. The experimental works were done at the rated engine speed of 1800 rpm.

Table 2. Technical specifications of the engine test bed

| Engine parameter | Specification |
|---|---|
| Make of model | Nissan SD22 Series |
| Injection system | Direct injection |
| Cylinder number | 4 |
| Displacement | 2164 cc |
| Bore | 83 mm |
| Stroke | 100 mm |
| Compression ratio | 22 : 1 |
| Cooling system | water |


Fig. 2. Engine test bed used in the experiments.

## 3. Results and Discussion

### *3.1. Brake thermal efficiency*

Fig. 3 shows the effect of load on the brake thermal efficiency for diesel fuel and WPO-diesel blends. The results show that increasing the engine load has the effect of increasing brake thermal efficiency as reported also by Kaimal and Vijayabalan [24] since at higher engine load the in-cylinder pressure would also be increased. As a result, the combustion temperature also increased resulting in higher thermal efficiency. It can also be seen from the figure that, WPO-diesel blends show slightly higher brake thermal efficiencies at 57-86% load compared with that of diesel fuel. The higher thermal efficiency of WPO-diesel blends is because of the low viscosity of WPO resulting a good mixture formation during premixed combustion phase as opposed to high viscosity fuel [25]. However, the difference was not significant as also reported by Gungor et al. [26]. At the full load condition, blending diesel with WPO did not change the thermal efficiency of the diesel engine. The maximum increase of the brake thermal efficiency by about 6.77% could be obtained at 71% load when blending with 20% WPO. WPO blend of 10% produced 3.09% increase of the brake thermal efficiency at the same load. Nevertheless, the difference of the brake thermal efficiency was not as high as another result [11]. This may be due to the calorific value of WPO which is found to be similar to that of diesel as can be seen in Table I. The thermal efficiency of the diesel engine strongly depends on the energy content of the fuel.

In contrast to the above results, the brake thermal efficiency of WPO-diesel blends was found to be lower than that of diesel fuel at the compression ratio of 17.5 as resulted by Mani et al. [12]. Reduction in the brake thermal efficiency by 1.9% was noticed at the full load for 100% WPO when compared to diesel fuel. The much lower reduction has been found by Kumar et al. [11] which has 23.12% of the brake thermal efficiency at the full condition for diesel fuel compared with 19.13% of the brake thermal efficiency for 20% WPO, which mean there was about 17% of the reduction in the brake thermal efficiency. The reason for this result is the fact that the calorific value of WPO used in their experiments was much lower than that of diesel fuel. Another reason is the higher compression ratio which is used in this study compared with the other studies which used 17.5 of the compression ratio. The higher compression ratio may increase the engine efficiency [19].

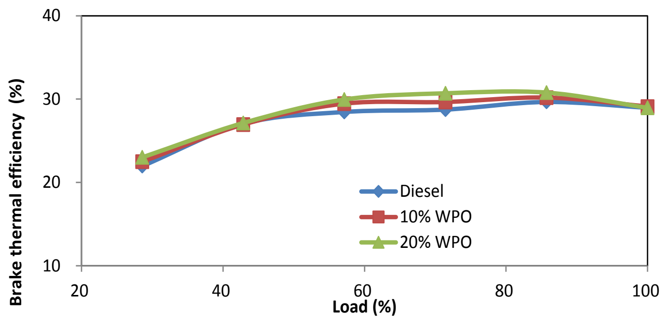


Fig. 3. Variation of brake thermal efficiency with the load.

### *3.2. Brake specific fuel consumption*

The changes of the brake specific fuel consumption (BSFC) with the load for diesel and WPO-diesel blends are presented in Fig. 4. BSFC is the parameter to measures how efficiently an engine is using the fuel supplied to generate work. BSFC varies from 369.6 g/kWh at a low load to 286.9 g/kWh at the full load for diesel fuel and it varies from 366.0 g/kWh to 282.8 g/kWh for 10% WPO, 355.8 g/kWh to 279.9 g/kWh for 205 WPO. It can be observed that the increases of the load have the effect to the decreases of BSFC for all fuels as expected. At the same time, it can also be observed that BSFC is slightly reduced when blending diesel fuel with WPO. Reducing BSFC means the increase of the thermal efficiency of the engine. However, the result also shows the similar BSFC at several loads due to the similar calorific value of WPO as previously discussed.

The different results have been found by the others [11]. The brake specific energy consumption became higher with the increase in the concentration of WPO in the blends. This is due to a low calorific value of WPO used in their experiments. In order to reduce BSFC and increase the thermal efficiency of the engine, some modification of the operating parameters can be done such as the injection timing and the injection pressure [9]. When the injection timing is retarded from $23^{o}$ bTDC (before top dead center) to $14^{o}$ bTDC, the BSFC was found to be lower while the thermal efficiency was found to be higher. Retarding the injection timing leads to the fast start of combustion which increases the mean effective pressure to do work.

### *3.3. Nitrogen oxides*

The oxides of nitrogen (NOx) is formed as a result of the oxidation of nitrogen in the air during combustion of the air-fuel mixture in the burning chamber. There are two sources of NOx emission including thermal and fuel NOx. Thermal NOx is decisive for total emission and all the reducing methods are targeted to reduce that component [27]. The formation of NOx is highly dependent on the in-cylinder temperature, the oxygen concentration and the residence time for the reaction to take place [15]. The variation of nitrogen oxides with the load is shown in Fig. 5. It was observed that the NOx emission increases with the increase of the load from 208 ppm at a low load to 331 ppm at the full load condition for diesel fuel and from 166 ppm at a low load to 287 ppm at the full load for 20% WPO. The increase of the NOx emission with the increase of the load is due to the increase of the in-cylinder temperature which can be observed by the increase of the exhaust gas temperature as shown in Fig 5. The increase of the in-cylinder temperature is caused by the increase of the peak pressure as the effect of the load increase.

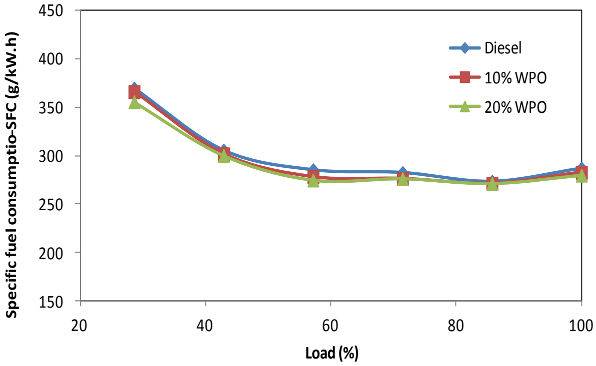


Fig. 4. Variation of brake specific fuel consumption with the load.

The figure also shows that the NOx emission was found to be lower by blending diesel with WPO. The decreased NOx emission is due to the decrease of the in-cylinder temperature as the effect of non-homogeneity of WPO which has a very broad range of carbon atom number. A similar result has been reported by Sudrajad et al. at various engine speeds [28] and Churkunti et al. [29]. There are some different methods widely used to minimize NOx from diesel engine i.e. the exhaust gas recirculation, the retarded injection timing, the stage injection of fuel, the fuel denitrogenation, the water injection, etc. The exhaust gas recirculation (EGR) is one of the most effective methods being adopted for reducing the NOx emission. The reduction in the NOx emission with the increase of EGR portion is due to the presence of inert gas (CO2 and H2O) in EGR system. These gases will absorb the energy released by combustion reaction, reducing the peak combustion temperature in the chamber [17]. The retarded injection timing also reduced the NOx emission for WPO [13].

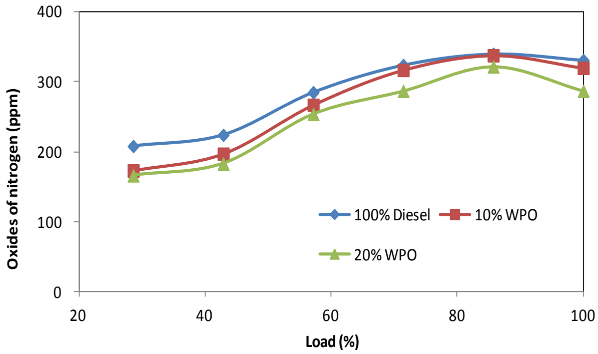


Fig. 5. Variation of nitrogen oxides with the load.

### *3.4. Unburned hydrocarbon*

Unburned hydrocarbon (HC) is a useful parameter to measure the combustion inefficiency consisting of fuel that is burned incompletely. The variation of unburned hydrocarbon with the load for blended fuels is shown in Fig. 6. The HC emission varies from 17 ppm at a low load to 3 ppm at the full load conditions for diesel and from 23 ppm at a low load to 5 ppm at the full load conditions for 20% WPO. It can be observed that the HC concentration of WPO is higher than that of diesel. Higher HC emission in WPO-diesel blends compared with diesel may be attributed to the reason that the fuel spray did not propagate deeper into the burning chamber. When the WPO blend fuel was injected and mixed with air, because of non-homogeneity of the air-fuel mixture, some local spots in the burning chamber will have the mixture which will be too lean to combust properly, and some fuel spots may be too rich with deficient oxygen to combust all the fuel [12].

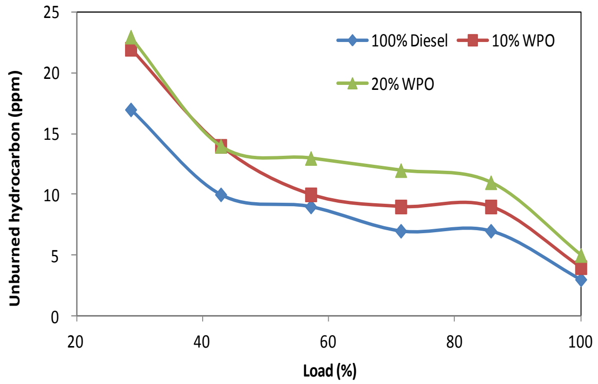


Fig. 6. Variation of unburned hydrocarbon with the load.

Unburned hydrocarbon emissions are also related to the volatility of fuel and the viscosity. High viscosities bring about larger droplet sizes and reduce the vapour pressure [11]. At a lower load, large amounts of the excess air, a low exhaust gas temperature, and lean fuel-air mixture regions may hold out to escape into the exhaust. The HC emission was decreasing with the increase of the load. At a low load, a high fuel supply also lead to higher hydrocarbon. The retarded injection timing may be applied for WPO to reduce the HC emission in diesel engines [13]. On the other hand, EGR may increase the HC emission since the reduction of oxygen content in the inlet charge. Lack of oxygen is responsible for the reduced oxidation rate causing incomplete combustion, hence higher HC emissions [17].

### *3.5. Carbon monoxide*

Fig. 7 shows the variation of the carbon monoxide (CO) emission with the load. The CO emission is primarily due to the lack of oxygen, mixture preparation, poor air entrainment, and incomplete combustion during the reaction process [12]. In general, diesel engine operates with lean mixtures and hence the CO emission will be low. CO is an intermediate product in the combustion of hydrocarbon fuels. Hence, the CO emission is greatly depended on the air-fuel ratio relative to the stochiometric proportions. The concentration of CO ranged from 269 ppm at a low load to 85 ppm at the full load conditions for diesel, whereas for WPO-diesel blends it varied from 281 ppm at a low load to 91 ppm at the full load for 10% WPO and from 295 ppm at a low load to 106 ppm at the full load for 20% WPO. The increased the CO emission is due to incomplete combustion as the effect of reducing the in-cylinder temperature, the poor mixture preparation, and local fuel-rich regions.

The figure also shows the reduced CO emissions at a higher load. The reason is that at a higher load, the in-cylinder peak pressure increased which increased the in-cylinder temperature. A higher combustion temperature will enhance the oxidation rate converting hydrocarbon fuel into carbon dioxides (CO2). Hence, the CO emission will be significantly reduced. However, at a lower load, the CO emission was also reduced. The reason is that at a lower load, the air-fuel ratio was high, which means there was more excess air that could be reacted with CO to produce CO2. The retarded injection timing and EGR could also be used to reduce the CO emission for WPO [13,17]. The retarded injection timing resulted in a higher heat release leading to complete combustion, whereas EGR raised the intake air temperature which can lead to a reduction of the CO emission.

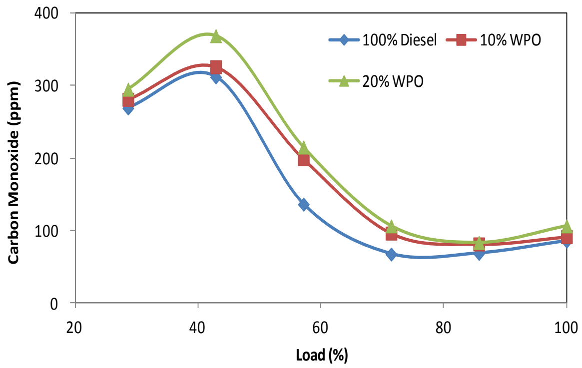


Fig. 7. Variation of carbon monoxide with the load.

*3.6. Smoke opacity*

Smoke are solid soot particles which is suspended in the exhaust gas. The smoke opacity is very important since it gives an indication of the concentration of pollutant leaving a smoke stack. Fig. 8 shows the effect of load on the smoke opacity for diesel and WPO-diesel blends. The smoke opacity ranges from 1.1% at a low load to 4.3% at the full load for diesel and from 1.1% at a low load to 5.5% at the full load for 20% WPO. It can be observed that the smoke opacity was almost similar at lower loads for all fuels. However, the smoke opacity for WPO-diesel blends was higher at higher loads. A higher smoke opacity produced in WPO-diesel blends may be due to the poor atomization of WPO. The larger size of fuel molecules contained in WPO is considered to result in poor atomization. Non-homogenity of WPO fuel will also affect the higher smoke of WPO fuel. The other reasons for a higher smoke opacity are a lower combustion temperature, reduced duration of combustion and rapid flame propagation.

Nevertheless, EGR and the retarded injection timing could not be used to reduce the smoke opacity for WPO. The smoke opacity was found to increase with the increase of the EGR percentage [21]. The reason is due to the partial replacement of air by exhaust gases, resulting in combustion instability. The retarded injection timing also increased the smoke opacity of WPO. Higher values of smoke opacity may be due to unburned and partially reacted hydrocarbons. A similar trend was also found when running diesel engines with waste tire pyrolysis oil [30,31].

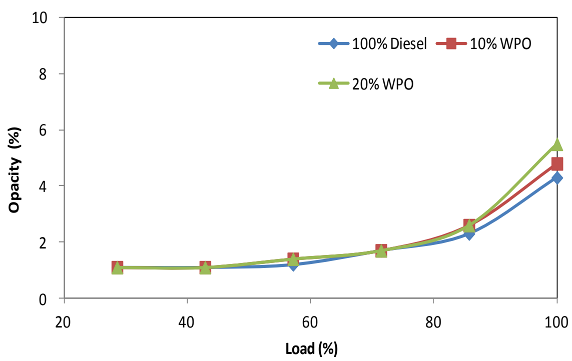


Fig. 8. Variation of smoke opacity with the load.

## 4. Conclusions

In this study, diesel engine tests have been done using diesel-WPO fuel blends under different loads to investigate the presence of WPO on the performance and emission characteristics of the engine. Brake thermal efficiencies are slightly higher as compared to that of diesel. However, the difference was not significant since the calorific value of WPO which is found to be similar than that of diesel. BSFC is slightly reduced when blending diesel fuel with WPO. Reduction of BSFC means the increase of the thermal efficiency of the engine as mentioned above.

The diesel-WPO fuel blends at various engine loads are found to have effects on the emissions of CO, NOx, HC, and smoke opacity. The NOx emission is found to be lower by blending diesel with WPO. The decreased NOx emission is due to the decrease of the in-cylinder temperature as the effect of non-homogeneity of WPO. The concentration of HC of WPO-diesel blends is higher than that of diesel. The higher HC emission in WPO-diesel blends compared with diesel may be attributed to the reason that the fuel spray does not propagate deeper into the burning chamber. The increased CO emission is due to incomplete combustion as the effect of reduced in-cylinder temperature, poor mixture preparation, and local rich regions. Finally, the smoke opacity is almost similar at lower loads. However, the smoke opacity for WPO-diesel blends is higher at a higher load. A higher smoke opacity produced in WPO-diesel blends may be due to the poor atomization of WPO. The larger size of fuel molecules contained in WPO is considered to result in poor atomization.

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