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A comparative study for the effects of synthetic diesel fuels on the performance and emissions of a single cylinder DI diesel engine

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ABSTRACT

The high cost of crude oil, the volatility of the international energy market, the nation energy supply security and the negative environmental impacts have been significantly stimulating the use of alternative fuel in engine applications. The production process of waste cooking oil and waste plastic to diesel-range paraffinic compositions was appropriately proposed according to the conditions of the socioeconomic situations. Two alternative synthetic diesel fuels from waste cooking oil and from waste plastic were successfully manufactured by Biomass R&D Centre of Chulalongkorn University, Saraburi, and had been used in this study. Pyrolysis (thermal cracking) process was implemented to break the long chain hydrocarbons, which is the main composition of waste plastics and waste cooking oil, to diesel range hydrocarbons. The main target of this research is to evaluate the influence of using two synthetic diesels and palm cooking oil biodiesel (palm methyl ester) on the performance, and emissions of a direct-injection single cylinder diesel engine comparing with conventional diesel fuel (CD) as base line. Test bench experiments (constant speed steady state) were conducted with a single cylinder DI CI engine at 1400, 1700 and 2100 rpm, along selected part load. The acquired data was a comparative analysis dealt with: brake specific fuel consumption, brake specific energy consumption, brake thermal efficiency, and exhaust emissions. The knowledge of these comparative results on engine performance obtained in this research can be used to develop high performance green fuels in a near future. The results provided a realistic experimental investigation in terms of using such alternative diesel fuels on diesel engines in Southeast Asian countries.

Keywords: *Direct Injection Diesel Engine, Synthetic Diesel, Waste Plastic, Waste Cooking Oil, Performance, Emissions*.

1. Introduction

Compression ignition engines (CI engine, diesel engines) have long been the dominant and workhorse engines of the industrial applications, favored for the exceptional fuel economy, which leads to higher thermal efficiency, and ability to provide power under a wide range of conditions. Therefore, diesel engines are widely used for transport and agricultural machinery in many regions of the world [1]. Despite of their advantages, they emit high levels of exhaust emissions (i.e., NOx and smoke) which significantly contribute to the environmental pollutions and health issues [2].

According to British Petroleum (BP), population and income growth are the key drivers behind growing demand for energy causing the world primary energy consumption to be projected to grow by 1.6% from 2011 to 2030, adding 36% to global consumption by 2030 [3]. Currently, a large portion of the world’s energy needs to be met by traditional fossil fuels. Due to depletion and higher cost of petroleum-based fuels beside the wide awareness of the environmental protection, researchers, globally, look for alternate fuels [4]. Recently, waste to energy is the trend in the selection of alternate fuels. Unconventional (or nonpetroleum derived) diesel fuels and synthetic fuels such as biodiesel from used cooking oil, and diesel fuel from plastics etc., are some of the alternative diesel fuels for the CI engines. Likely, such alternative diesel fuels are becoming major issues in the consciousness of oil importing countries [5, 6].

Biodiesel, which is commercially produced from virgin vegetable oils, has been accepted as a suitable alternate to diesel fuel, and it has become in recent years a subject for debate around the world as well as in the Southeast Asian countries in order to reduce the dependency on foreign oil [7]. However, the main limiting factor for the market diffusion of biodiesel is the high economic cost of production compared to petroleum diesel oil. The major economic factor to consider for the input costs of biodiesel production is the feedstock due to the higher cost of virgin vegetable oil, which is about 80% of the total operating cost [8]. This led to search for feedstoke which provides the advantage of the lower cost and sustainability.

Accordingly, due to the production of large quantities of waste cooking oil, a substantial amount of biodiesel can be produced from which. Therefore, substantial portion of the biodiesel can be replaced by the biodiesel obtained from waste cooking oil [7]. Waste cooking oil (WCO) as a cheap feedstock is considered highly environmentally sustainable since WCO is a waste product from domestic and commercial cooking processes and then recycled to a transportation fuel [9].In addition, it avoids the conversion of land use for crop production and the import of virgin oil as feedstock.

Typically, four methods to reduce the high viscosity of vegetable oils to enable their use in common diesel engines without operational problems such as engine deposits have been investigated: blending with petrol diesel, pyrolysis, micro emulsification, and transesterification [10]. The two most popular techniques are transesterification and pyrolysis however; the focus has been on the production of bio-diesel via transesterification [11]. Waste cooking oil with long chain of palmitic acid and oleic acid has the potential to be cracked by thermal cracking or catalytic cracking for possible formation of hydrocarbon chain using the pyrolysis technology. To create biodiesel, a fuel with a viscosity closer to diesel, oil can be modified. Thermally cracking, or controlled pyrolysis, of bio-oil decreases its molecular weight and is there by effective in converting oil to a more useable fuel, like biodiesel. Biodiesel via pyrolysis has some advantages against the one, which is produced via the typical transesterification process. Some but not the least are the absence of using alcohols, cleaning water and the very similar properties to the commercial diesel. In addition, the properties of the biodiesel from waste cooking oil would be largely dependent on the physicochemical properties of feedstock [7].

Plastic shave become an indispensable part in today’s world, due to their light weight, durability, energy efficiency, coupled with a faster rate of production and design flexibility, these plastics are employed in entire gamut of industrial and domestic are as hence plastics have become essential materials and their applications in the industrial field are continually increasing. At the same time, waste plastics have created very serious environmental challenge because of their huge quantities and their disposal problems [12,13,14].Waste plastics do not biodegrade in landfills, are not easily recycled, and degrade in quality during the recycling process. Instead of biodegradation, plastics waste goes through thermal treatment and fuel can be derive, by adopting the chemical process such as Pyrolysis can be used to safely convert waste plastics in to hydrocarbon fuels that can be used for transportation [15]. Moreover, both plastics and petroleum derived fuels are hydrocarbons that contain the elements of carbon and hydrogen. The difference between them is that plastic molecules have longer carbon chains than those in LPG, petrol, and diesel fuels. Therefore, it is possible to convert waste plastic into fuels.

Unfortunately, fuels do have different chemical and physical properties compared to fossil diesel fuel have to be considered. Some fuel properties required by the standards. The above fuels' properties affect the whole combustion process and thereby the engine performance and emissions. In contrast to the engine's demand for fuels with defined properties to meet the emission targets.

The motivation of this research is to investigate and compare the effect of different synthetic and alternative diesel fuels to the conventional diesel fuel in terms of their performance and emissions characteristics. These fuels include pyrolysis waste plastics diesel (PWPD) which produced by well-sorted polyethylene (PE) and polypropylene (PP) waste plastics; pyrolysis waste cooking biodiesel (PWCOB) using waste cooking oil as a feedstock; and palm cooking oil biodiesel (Palm methyl ester, FAME BD). The experiments were performed using a single-cylinder, direct-injection diesel engine that is used for general purposes. Comparatively, Thai conventional diesel fuel (CD) was used as a base line.

2. Experiment Setup and Tested Fuels

2.1. Experiment Setup and test method

The schematic diagram of the experimental setup is shown below in Fig.1.A commercial diesel engine, type KUBOTA RT140 was implemented in this experiment. The engine remained unmodified during the whole experiment with all testing fuels. The engine specification is listed in Table 1.

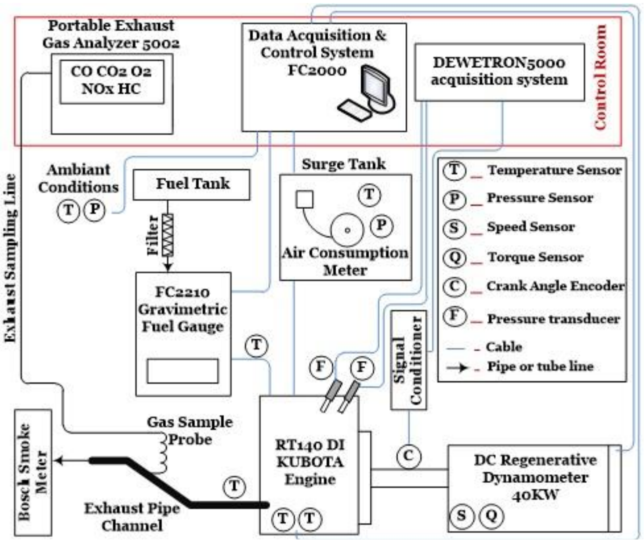

Fig.1: Schematic diagram of the experimental setup.

The engine was coupled to a 40KW DC regenerative dynamometer type (LAK 4180-AA), which fully controlled by FC2000 control system to precisely vary engine speed and torque, and measure other performance parameters. The average air mass flow rate over the entire engine cycle (quasi-steady) measured based on the Air Box method using a TH01-40 air consumption meter. An accurate combined ambient conditions sensor was used for measuring the ambient conditions (pressure, temperature, and relative humidity) of the air in the testing room. The average gravimetric fuel consumption rate was measured by the FC2210 Advanced Fuel Measurement Device (Gravimetric Fuel Gauge). The major emissions of carbon monoxide (CO), carbon dioxide, unburned hydrocarbons (HC) and nitrogen oxides (NOx), were measured with a Portable Exhaust Gas Analyzer type EMS 5002. The diesel smoke evaluator (ETD 020.50) was used along with the diesel smoke tester (ETD 020.00) to indicate the smoke opacity.

The accuracies of the measuring instruments and the EMS 5002 emission analyzer are listed in the Table 2.

Table 1: Kubota engine specifications.

Items	Specification Parameters
Engine Model & Type	Kubota-RT140, Naturally aspirated, Water-cooled, Single cylinder, and 4-cycle DI diesel engine
Cylinder bore ×Stroke × Displacement(mm)	97 × 96 × 709
Continuous rated power output (kW/rpm)	9.2/2400
Max. power/engine speed (kW/rpm)	10.3/2400
Max. torque/engine speed (N.m/rpm)	49.0/1600
Compression ratio	18:1
Injection nozzle type	Bosch KBAL type (4 holes nozzle)
Nozzle opening pressure (Bar)	215.75
Injection timing (Deg CA)	18.5° (BTDC)

Table 2: The measuring instruments and EMS 5002 exhaust gas analyzer.

Measurements	Accuracy	Measurement Ranges
HC	±4ppm	0 – 2000 ppm
NO	±25ppm	0 – 5000 ppm
CO	±0.06%	0 – 10%
CO_2	±0.3%	0 – 20%
O_2	±0.1%	0 – 25%
Fuel consumption	± 0.4 % full scale	
Speed measuring	±1 rpm	
Temperature	±1°C	

The test method used in this study was modified-steady-state operating points based on the European Stationery Cycle (ESC) 13-modes (Fig.2)[26]. Points 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13 represent the selected high probably operating points along the ESC driving cycle. Engine speeds A, B, and C was expected to be 1400, 1700, and 2100 rpm, respectively. In addition, the low, medium, and high loads were approximately considered to be 11, 23, 35 N.m, respectively.

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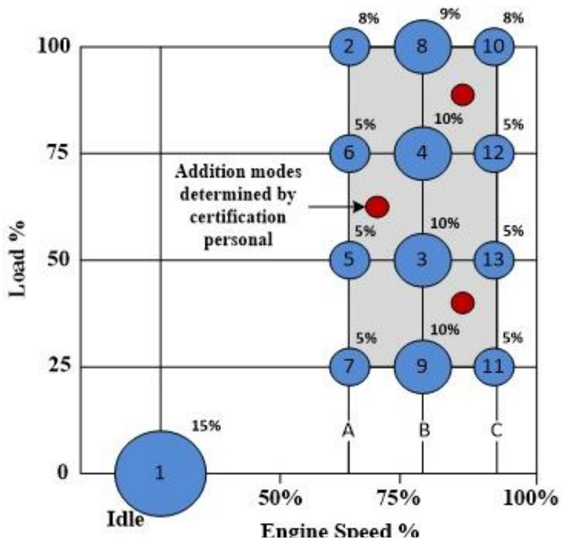

Fig. 2: European stationary cycle (ESC).

2.2. Tested Fuels

The chemical compositions and the properties of interest of the testing fuels are listed in Table 3. In addition, the elemental percent analysis and the simulated distillation curves are provided in Table 4 and Fig.3, respectively as it was direct measured or calculated/predicted from their composition by liquid chromatograph method.

Table 3: Physical properties of the tested fuels.

Property	**Test Method**	**CD⁽³⁾**	**PWPD**	**PWCOB**	**FAME BD**
Density at 15 ˚C (kg/m³)	ASTM D1298	827.5	833.3	820.3	876.703
Kinematic viscosity at 40˚C (mm²/s)	ASTM D445	3.74	4.70	2.92	5.36
Heating Value (MJ/kg)	ASTM 04-5865	44.86	45.45	44.48	39.510
CHN elements Carbon (%wt) Hydrogen (%wt) Nitrogen (%wt)		 81.17 15.29 0.066545	 76.24 14.08 0.061415	 77.14 14.60 0.077545	 72.265 13.69 0.412125
API Gravity	ASTM D1298	39.5	38.3	41.0	29.9
Distillation (˚C) IBP T10 T50 T90 FBP	ASTM D86	 206.59 251.70 316.18 375.34 398.21	 250.29 304.93 329.60 360.01 376.47	 221.61 265.56 310.46 401.62 449.71	 306.09 346.29 350.71 352.57 358.47
Cetane Index⁽¹⁾	ASTM D4737	56.8	64.9	59.4	N.D(2)
Flash Point (˚C)	ASTM D92	81.5	96.0	93.5	180.0
Fire Point (˚C)	ASTM D92	85.0	126.0	103.0	185.5

(1) The report on Cetane Index (from Fuel test lab, Division of fuel quality, Department of Energy Business, Ministry of Energy), Thailand.
(2) FAME BD Cetane Index cannot be determined.
(3) The conventional diesel fuel is subjected to the Thai policy blended with 5% of palm methyl-easter (PME).

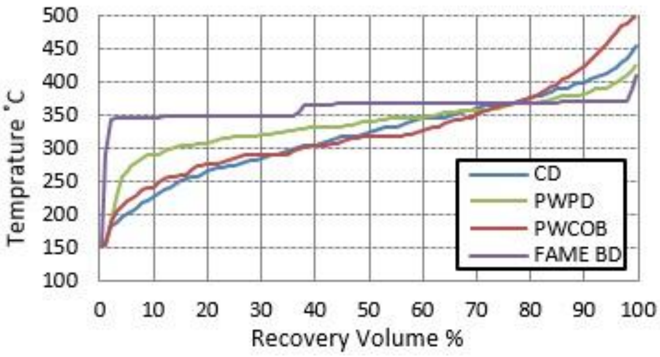

Fig.3: Simulated distillation curves.

Table 4: Elemental percentage analysis.

Contents	**CD**	**PWPD**	**PWCOB**	**FAME BD**
Naphtha	5.0%	2.35%	2.83%	0.67%
Kerosene	10.0%	1.46%	8.67%	0.18%
Diesel: -Light gasoil -Gasoil	(63.0%) 50.0% 13.0%	(78.69%) 58.69% 20.0%	(66.75%) 58.5% 8.25%	(96.15%) 35.65% 60.5%
Long residue	22.0%	17.5%	21.75%	3.0%
Total	100%	100%	100%	100%

3. Results and Discussions

3.1. Performance Test

3.1.1. Brake Specific Fuel Consumption (BSFC)

Brake specific fuel consumption (BSFC) measures how efficiently an engine is using the fuel supplied to produce work. It is inversely proportional to thermal efficiency and has units of grams per kilowatt-hour (g/kWh). It is also a function of fuel consumption and engine power output. Fig.4 shows the variations of the BSFC of the test fuels at all engine speeds with respect to engine loads. In general, at all engine speeds, BSFC decreases with increase in the engine load. The main reason for this could be that the percent increase in fuel required to operate the engine is less than the percent increase in brake power due to relatively less portion of the heat losses at higher loads.

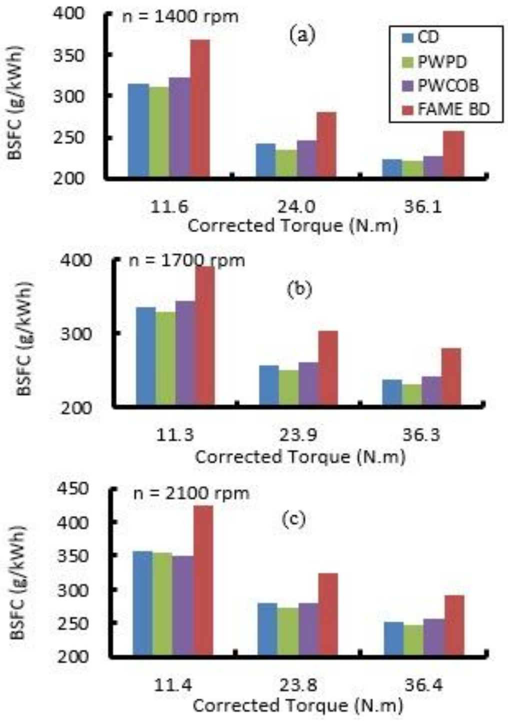

Fig.4: Brake specific fuel consumption.

From Fig.4,BSFC decreases as the load increases for all the fuels. On the total average and in comparing with commercial diesel (CD), brake specific fuel consumption for the pyrolysis waste plastic diesel (PWPD) decreased by 1.52% while increased for pyrolysis waste cooking oil biodiesel (PWCOB) and FAME biodiesel (FAME BD) by 0.94% and 12.65%, respectively. This variation in BSFC mainly attributed to the different amounts of fuel (FC) which is necessary to deliver the same power output at every operating condition. The alterations in the BSFC dominantly due to the consequence of the different heating values of the test fuels (refer to Table 3).

3.1.2. Brake Specific Energy Consumption (BSEC)

The brake specific energy consumption (BSEC) is defined as the energy of fuel needed to produce 1 kWh of brake work. It is an indication of the energy needed to produce the same required power. Fig.5 shows comparisons of BSEC for the test fuels at all operating conditions. As it can be seen from the figure, regardless of engine speed, BSEC decrease with load increase. On average, PWPD shows the best energy economy with a lower BSEC by 0.55% than CD. PWCOB provides similar BSEC which 0.29% higher than CD. The highest BSEC was shown by FAME BD with 2.19% higher than CD. Beside the effect of the heating values of the test fuels on the fuel consumption, the higher kinematic viscosity of FAME BD fuel could also affect its spray characteristics and consequently the whole combustion process and fuel consumption.

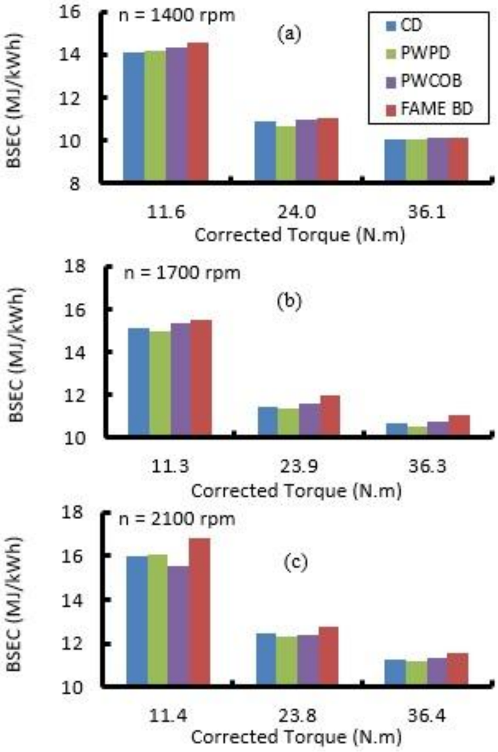

Fig.5: Brake specific energy consumption.

3.1.3. Brake Thermal Efficiency (BTE)

Fig.6 illustrates brake thermal efficiency (BTE) with CD, PWPD, PWOCB, and BD fuels at all engine speeds. Brake thermal efficiency evaluates how efficient the engine transforms the chemical energy of the fuel into useful work. It is determined by dividing the brake power of the engine to the amount of energy input to the system. As expected that for all engine speeds, the brake thermal efficiency was higher in the case of medium and high-load conditions (23 and 35 N.m) compared to low load condition (11 N.m). This can be explained by that less fuel energy is needed to cover the mechanical losses of the engine when the engine load is increased.

It can be observed from Fig.6 that there is no significant difference in the BTE for PWPD and PWCOB fuels in compare with CD. Averagely, PWPD shows a slightly higher value of BTE by 0.75% while PWCOB gives slightly lower value by 0.37% compared to that of CD at all engine operating conditions. The main reasons are the corresponding higher and lower heating value of PWPD and PWCOB, respectively. The heating value of PWPD is higher by 1.31% and the corresponding heating value of PWCOD is lower by 0.85% than that of CD. The combination of fuel consumption and heating values results in small variations of BTE among the CD, PWPD and PWCOB fuels. On the other hand, FAME BD shows the lowest BTE with a reduction of 2.82% compared to CD. The reduction in thermal efficiency with FAME BD attributed not only to the lower heating value of FAME BD, which is 11.93% less than of that of CD, but also to the higher viscosity. Higher viscosity resulted in poor spray characteristics and air to fuel mixing.

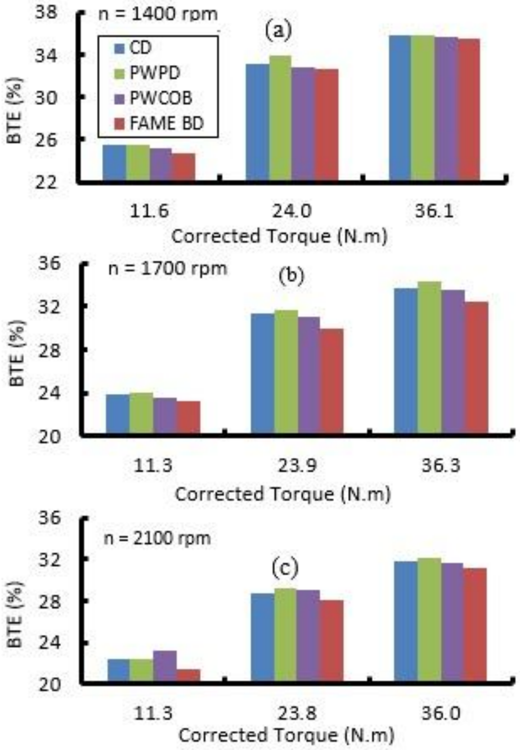

Fig. 6: Brake thermal efficiency.

3.1.4. Exhaust Gas Temperature

Engine exhaust temperature is an important indicator of the cylinder combustion temperature, and it is hence a good parameter in analyzing the exhaust emissions especially for NOx. Furthermore, the exhaust gas temperature is a convenient scale to study the extent of afterburning. The variations of the gases exhaust temperature with the engine speeds and load range for all the test fuels shown in Fig.7.

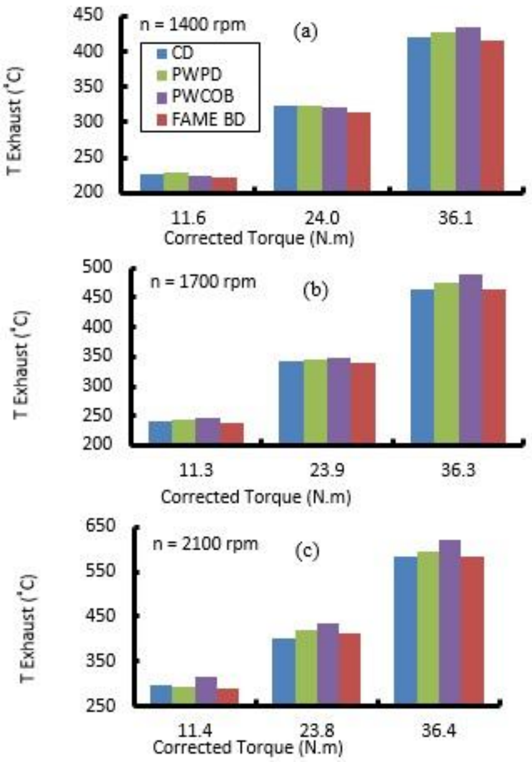

Fig.7: Exhaust gas temperature.

It is shown from the figure at each engine speed that the exhaust gas temperature increases with load because more fuel is burnt to meet the power requirement. In addition, it was observed that the exhaust gas temperature was reasonably higher for PWPD and PWCOB whereas it was lower for FAME BD compared to the baseline CD.

Averagely, the exhaust gas temperature increase in the case of PWCOB and PWPD varies approximately from 4 to 31 ˚C and 4 to 10 ˚C, respectively, whereas the exhaust gas temperature reduction in the case of FAME BD was up to 7 ˚C comparing with CD. By the same meaning, the exhaust gas temperature was approximately higher by 2.65% for PWCOB and 1.03% for PWPD while lower by 1% with the FAME BD fuel. The higher exhaust gas temperature in the case of PWPD and PWCOB compared to CD is due to higher rate of heat release during the latter of expansion where some fuel mixtures tend to burn; consequently, afterburning occurs (see the ROHR curves). In addition, the higher distillation temperature (T90) of PWCOB among the test fuels may contribute to the higher exhaust temperature (see Table 3).

The lower value of exhaust temperature may also suggest that the engine was not thermally overloaded when operating on biodiesel although more fuel was input in order to keep the same power output from engines. Another possible explanation of the lower value of exhaust temperature could be because FAME BD has got lower heating value and higher certain number than diesel fuel. Ignition delay occurred in fewer periods because of higher cetane number resulting in decrease in exhaust temperature.

3.2. Exhaust Gas Emissions Test

3.2.1. Hydrocarbons (HC)

Hydrocarbons are the consequence of incomplete combustion of the hydrocarbon fuels. It is widely accepted that the hydrocarbon emissions are mainly caused by over-mixing (i.e. mixing fuel with air to rations that are leaner than the flammability limit) during ignition delay and by under-mixing (insufficient mixing of the fuel and air in close the nozzle orifices) during expansion.

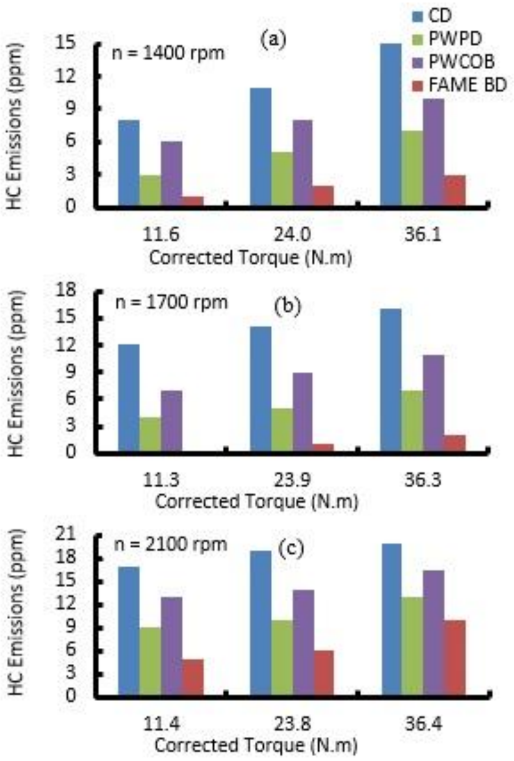

Fig.8: Hydrocarbon (HC) emissions for CD, PWCOB, PWPD and FAME BD at (a) 1400 rpm, (b) 1700 rpm, and (c) 2100 rpm.

Fig.8 presents the variations of the HC emissions for CD, PWPD, PWCOB and BD at engine loads and speeds. The result demonstrates that, at overall engine operating conditions, all fuels produce very low HC emissions, and the speeds have no significant effect on the emission. It is also noticed that, as the load increases, HC emissions of all test fuels increase, gradually. The increase in the HC emissions with the increase in engine load is mainly attributed to the change in the air fuel ratio. As it well known, increasing engine load causes a reduction in the air fuel ration. Thus, it enhances the under-mixing process and consequently increases the HC emissions.

It can be seen that all test fuels yield to lower HC emissions than CD. PWCOB, PWPD, and FAME BD fuels on average at all partial-load test conditions reduce the HC emissions by approximately 28.54%, 54.11%, and 79.85%, respectively, in comparison with conventional diesel. The HC reduction probably because the alternative fuels have higher cetane number, which generally reduces ignition delay period and over-mixing, hindering the formation of HC emissions. In addition, the reductions in HC emissions with PWCOB and FAME BD are also due to the fuel oxygen content, resulting in improved combustion. Furthermore, the lower density of PWCOB and the higher volatility of PWPD with that of the CD improve the spray characteristics and accelerate the mixing process, hence, decreasing HC. Lastly, cleaner combustion with the utilization of PWCOB, PWPD, and FAME BD fuels can be concluded from the results of HC emissions.

3.2.2. Nitrogen Oxides Emissions (NOx)

Nitrogen oxides are created during the combustion process at high-temperature from the nitrogen presence in the air and/or from the nitrogen found in fuel. The formation of NOx is dependent on temperature, local oxygen concentration, and residence time (the time period in the combustion cycle spent at high-temperature). NOx steadily increase as air ratio decreases due to the increase in fraction of cylinder contents being burnt close to stoichiometric during combustion, and also due to higher peak temperature and pressure.

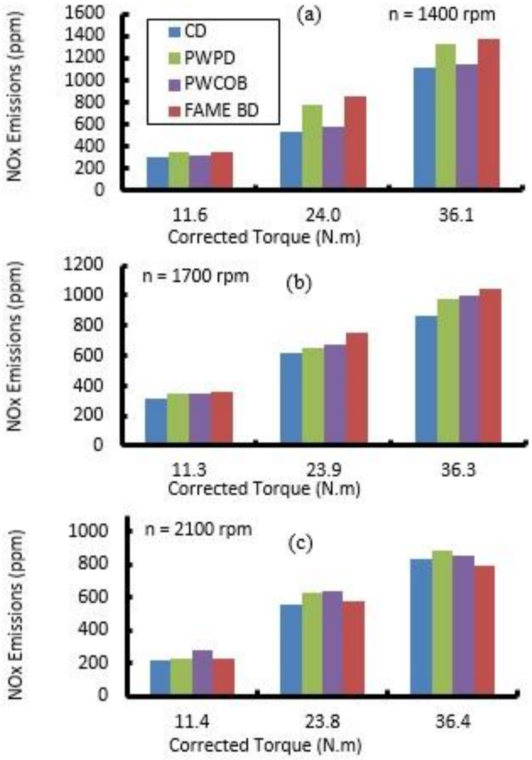

Fig.9: Nitrogen oxides (NOx) emissions for CD, PWCOB, PWPD and FAME BD at (a) 1400 rpm, (b) 1700 rpm, and (c) 2100 rpm.

The variation of NOx emissions with the PWPD, PWCOB, FAME BD, and CD under all engine conditions are shown graphically in Fig.9. As shown in the figure, NOx emissions of all test fuels increases gradually when the engine load increases. This is due to the significant increase in the exhaust temperature as it was mentioned above. It also found that all the alternative fuels emit higher NOx concentrations in compare with CD. Among the test fuels, FAME BD showed the highest NOx concentrations. The average increase in NOx emissions compared to CD fuel for PWPD, PWCOB, and FAME BD fuels was 15.26%, 10.77%, and 17.58% respectively.

The increase in NOx emissions with all the test fuels in compared with CD fuel can be explained as follows:

- One reason for the increased NOx in PWCOB and FAME BD fuels compared to CD may be the oxygen content in these biodiesels, which enhance the local oxygen concentration and consequently promote better combustion and thus the formation of NOx emission. Similarly, PWPD fuel may contain some oxygenated hydrocarbons according to [2,27]. Another factors that cause the increase in NOx could be the lighter of PWCOB cause the better spray atomization thus the higher peak temperature resulted during the combustion process of PWCOB in compared to CD.
- In the case of PWPD fuel, the higher volatility leads to better combustion efficiency and consequently higher peak temperature resulted which promotes the NOx formation.
- The higher percentage of unsaturated fatty acids composition of FAME BD, which contains double bonds in the carbon chain, may be an additional reason for higher NOx emissions.

3.2.3. Carbone Monoxide Emission (CO)

Carbon monoxide (CO) emission is toxic and must be controlled. Generally, CI engine operates with lean mixtures and hence the CO emission would be very low. Moreover, CO emission represents lost chemical energy from the fully utilization of fuels' energy. It is believed that CO emissions result from the lack of oxygen, poor air entrainment, mixture preparation and incomplete combustion during the combustion process. Emission of CO is therefore greatly dependent on the equivalence ratio. Rich mixture results in higher CO.

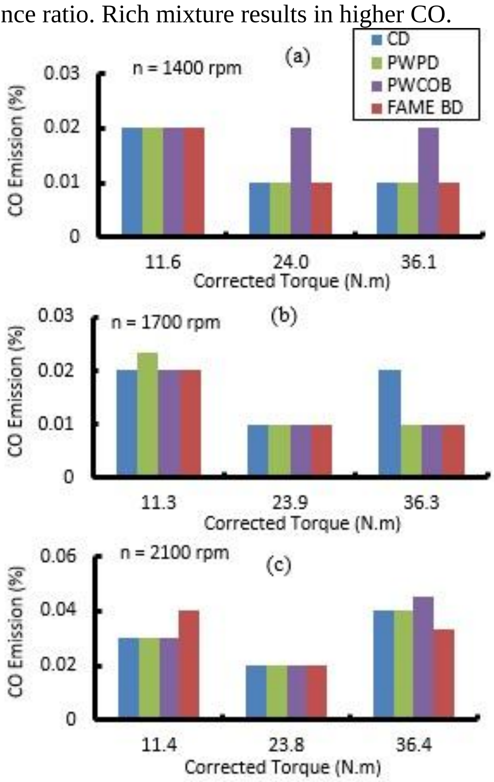

Fig. 10: Carbon monoxide (CO) emission for CD, PWCOB, PWPD and FAME BD at (a) 1400 rpm, (b) 1700 rpm, and (c) 2100 rpm.

The comparison of CO emission with CD, PWPD, PWCOB, and FAME BD fuels is shown in Fig.10. It can be seen from the results that the trends of CO emissions from the engine fueled with different fuels are similar to each other. The amount of engine has emitted CO emissions at low and medium loads are low; but are high at the full loads. The main reason for this phenomenon is due to the higher amount of injected fuel at engine full load than that at low and medium load resulting in the poorer spray atomization that causes larger amount of fuel rich zone that lack of oxygen in the spray combustion processes. In consequence, it caused more CO generated during incomplete combustion processes.

In addition, the some incomparable variations of CO emission might be due to the low accuracy of the exhaust analyzer. In general, it was noticed that the detected CO concentrations of the test fuels at partial loads are less than 0.06%, which represents the accuracy of the CO sensor of the emission analyzer.

3.2.4. Carbon Dioxide Emissions (CO2)

Carbon dioxide emission (CO2) is an indication of complete combustion; therefore, the higher CO2 represents better combustion efficiency. Fig.20 depicts the variation of CO2 emission with load for PWPD, PWCOB, FAME BD and CD at speed of 1400 rpm, 1700 rpm, and 2100 rpm. From the results, the CO2 emissions with all tested fuels increases nearly linearly as the engine load increases due to higher in-cylinder pressures and temperatures which lead to more completed and efficient combustions. Moreover, it is observed that the amount of CO2 produced while using PWPD, PWCOB, and FAME BD fuels is lower than CD at all loads with different engine speeds. In compare with the baseline CD, CO2 emissions for PWCOB, PWPD, and FAME BD fuels decreased averagely by 4.88%, 5.52%, and 8.06 %, respectively. The CO2 emissions results are good indications of more complete combustion in the case of using the alternative diesel fuels. The increase in CO2 emissions with the PWPD, PWCOB, and FAME BD fuels were mainly due to the presence of oxygen in the chemical structure of the fuels.

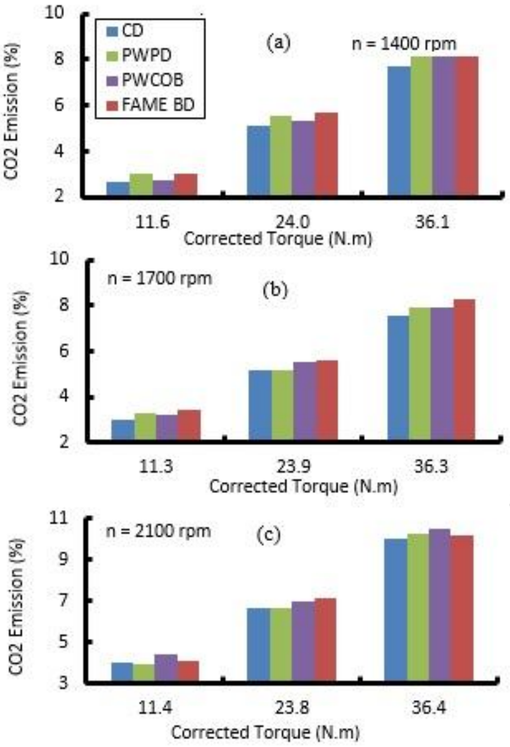

Fig.11: Carbon dioxide (CO$_2$) emissions for CD, PWCOB, PWPD and FAME BD at (a) 1400 rpm, (b) 1700 rpm, and (c) 2100 rpm.

3.2.5. Smoke Opacity

Smoke is nothing but solid soot particles suspended in exhaust gas. It mainly originates from pyrolysis and incomplete combustion of fuels at in homogeneous mixture conditions.

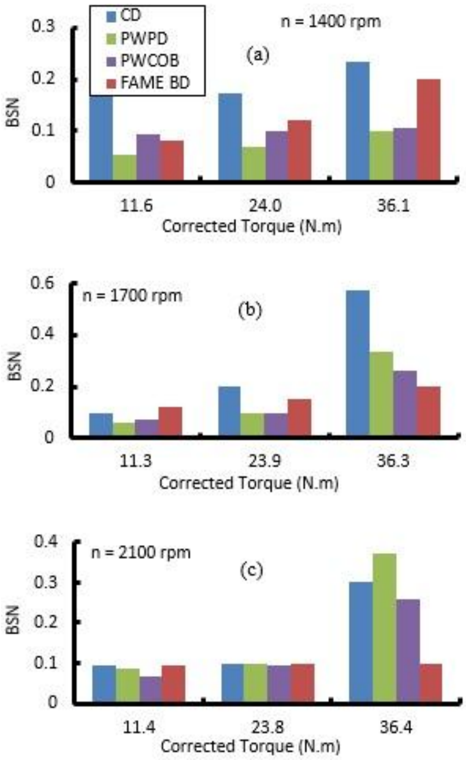

Fig. 12: Smoke opacity for CD, PWCOB, PWPD and FAME BD at (a) 1400 rpm, (b) 1700 rpm, and (c) 2100 rpm.

Fig.12 demonstrates the smoke opacity (Bosch Smoke Number, BSN) for CD, PWPD, PWCOB, and FAME BD. From figure below, smoke for baseline CD fuel is the maximum throughout the load range with significant lower values for the other comparative fuels. On average and relative to CD, 35.60% lower smoke emissions were observed with PWPD fuel and for PWCOB operation 33.25% lower smoke emissions were produced. In the case of FAME BD 25.79%, lower smoke emissions. The reductions in smoke emissions with PWCOB and FAME BD were associated with the oxygen content in the fuels. The oxygen content in the alternative fuels made the local fuel rich mixture to fuel lean mixture. The oxygen enhanced better combustion, which is resulted in reduced smoke emission. In the case of PWPD operation, the reason for the reduced smoke is the availability of premixed and homogeneous charge inside the engine well before the commencement of combustion. Higher combustion temperature, extended duration of combustion and rapid flame propagation are the other reasons for reduced smoke [12]. Another reason for lower smoke may be better and complete combustion of fuel due to the higher volatility of the PWPD fuel. From these results, it can be concluded that the use of PWCOB, PWPD and FAME BD are generally cleaner as they results in lower black smoke emission.

4. Conclusion

In the present work, the effects of two synthetic alternative diesel fuels (pyrolysis waste plastic diesel, PWPD and pyrolysis waste cooking oil biodiesel, PWCOB) on the engine performance and emissions and characteristics over a wide range of engine operating conditions were well investigated. Besides that, further comparing was done using FAME BD from palm cooking oil (palm methyl ester). Experiments were carried out on single cylinder KUBOTA RT140 diesel engine. From the research objectives, the implementation of the research and the results, conclusions can be drawn out as follows:

- The two synthetic diesel fuels showed very acceptable performance characteristics in compare with the conventional diesel fuel. These performance characteristics presented by an average improvement in the BSFC, BSEC, and BTE by 1.52%, 0.55%, and 0.75%, respectively, in the case of PWPD, whereas slightly reductions in the mentioned performance characteristics were observed with PWCOB by 0.94%, 0.29%, and 0.37% ,respectively.
- At all operating conditions the HC emissions are averagely lower for PWCOB, PWPD and FAME BD by 28.78%, 54.11%, and 79.85%, respectively, compared to those of CD.
- Under all the engine operating conditions both at low speed and high speed as well as both at partial loads and full load, the NOx emissions produced by PWCOB, PWPD and FAME BD are slightly higher. Specifically, in average at partial load conditions NOx was higher by 10.77%, 15.26%, and 17.58%, respectively compared to CD.
- Engine black smoke was significantly reduced with all the PWCOB, PWPD and FAME fuels by 35.61%, 33.26%, and 25.8%, respectively, at partial load conditions.
- At a fixed engine speed, the CO_2 emission with all tested fuels increases nearly linearly as the engine load increases while. The average increasing in the CO_2 emissions with PWCOB, PWPD and FAME BD at partial load conditions was by 5.52%, 4.88%, and 8.06%, respectively.
- The trends of CO emissions from the engine fueled with different fuels are similar to each other. The amount of engine has emitted CO emissions at low and medium loads are low.
- FAME BD showed an expected results based on some previously research done.
- The operating ability of the engine to be run with such synthetic diesel fuels under a wide range of operating conditions and without any engine’s modifications indicates that the PWPD and PWCOB are good alternative fuels for diesel and therefore must be taken into consideration in the future for transport purpose.

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