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Combustion Performance and Exhaust Emission Analysis of Diesel Engine using Waste Cooking Oil

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Abstract – *The primary goal for this paper is to investigate the effect of biodiesel from WCO on combustion performance and exhaust emission analysis of a direct injection diesel engine. The experiment has been conducted at variable engine speed, constant load and at compression ratios of 17.7. Three types of biodiesel from WCO are tested, which consist of different blending ratio percentage (5%, 20% and 100%) and labelled as B5, B20 and B100 respectively and diesel was used as a comparison purposes. In the end, results show that B5 and B20 show a close resemblance with diesel especially in terms of exhaust emissions.*

Keywords: Biodiesel, Combustion, Diesel Engine, Exhaust Emission, Waste Cooking Oil

1.0 INTRODUCTION

In present time, the extensive usage of diesel engines has led to an increase in demand for diesel fuel. At the same time, the demand towards energy continues to increase year by year and cause the depletion of the oil reserves. As a result, biodiesel has drawn exceptional attention from researchers as a potential alternate fuel for diesel. Biodiesel is one of renewable and alternative fuel which consists of fatty acid methyl esters (FAME). It is produced through transesterification process, where an ester compound is exchanged by an alcohol and catalysed by the adding of acid or base. Apart from sustainability, biodiesel also a non-toxic fuel, biodegradable, environmentally friendly and oxygenated. It is surrounded by 11% oxygen per weight [1] and this is a good property as it could lead to complete combustion process and shrinks its oxidation potential. However, the cost of edible oil as biodiesel feedstock is expensive and also received condemnation due to the superfluous clearing of forests for plantation purpose when the demand for edible oil for human is still increasing [2].

Waste cooking oil (WCO) is one of the practical solution in reducing the feedstock cost for biodiesel production and it is known for its high content of water and free fatty acid by the presence of heat and water [3]. The use of biodiesel from WCO as a diesel substitute in diesel engine have been reported in many research studies and most of them found that harmful exhaust emissions decreased with equivalent engine performance at low blending ratio [4-8].

Moreover, compared to conventional diesel, biodiesel including from WCO produced higher peak pressure due to its lower ignition delay and thus resulting in earlier combustion [9]. High peak pressure as well as the maximum rate of increase in pressure rise indicates that a large amount of fuel burned in premixed combustion stage. However, different percentage of biodiesel blends may result in different characteristics. In conjunction with these phenomena, the motivation of this present study is to analyse and compare the in-cylinder combustion pressure and exhaust emission characteristics of various percentage biodiesel blends from WCO.

2.0 METHODOLOGY

For this research study, three types of biodiesel blends from WCO have been used for engine testing namely B5, B20 and B100 and all of them were compared with diesel. B5 comprises of 5% WCO biodiesel with 95% of diesel, and B20 comprises of 20% WCO biodiesel and 80% diesel, while B100 is a 100% WCO biodiesel without any addition with diesel. The measurement of the fuel properties was conducted in order to ensure that all biodiesel complied with ASTM biodiesel standard. The details of the biodiesel specification are shown in Table 3. The engine testing was operated for about an hour at five different speeds, which were 1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm and 2400 rpm with constant load of 20Nm.

Table 3: Testing fuel specifications

Parameter	**ASTM D6751**	**B0 Diesel**	**B5 WCO**	**B20 WCO**	**B100 WCO**
Density (g/cm^3)	0.88	0.843	0.844	0.851	0.882
Kinematic Viscosity at 40°C (mm^2/s)	1.9-6.0	3.718	3.754	3.829	4.282
Calorific Value (MJ/kg)	N/A	42.32	42.08	38.67	35.02
Cetane Number	> 46	46.6	46.9	48.9	57.7
Acid Number (mgKOH/g)	Max 0.5	0.270	0.270	0.280	0.340

The schematic diagram of the engine testing setup is shown in Figure 1. The type of engine used is a YANMAR TF120, single cylinder, four stroke, naturally aspirated with water cooled, direct injection diesel engine. The other basic specifications of the engine are listed in Table 1. The fuel control unit was placed next to the engine fuel pump and it was separated in two different tanks, called diesel fuel tank and alternative fuel tank. The engine is coupled with NBK coupling to a positive displacement gear pump which functions as a hydraulic dynamometer in order to load the engine. The instrumentation for measuring engine performance consists of a piezo electric transducer which installed in the cylinder head and used to measure in-cylinder pressure inside the combustion chamber. In addition, the crank angle encoder was used to record the crank angle degree of the rotating crank angle. The data taken from both sensors are transmitted and analyzed by TFX Engineering data acquisition. Parameters that produced from this system included in-cylinder pressure, maximum combustion temperature, indicated power and torque, as well as exhaust temperature. The experimental study was done according to the SAE J1349 standard. Engine testing was repeated for several times before the actual testing in order to ensure that all instruments were in stable condition.

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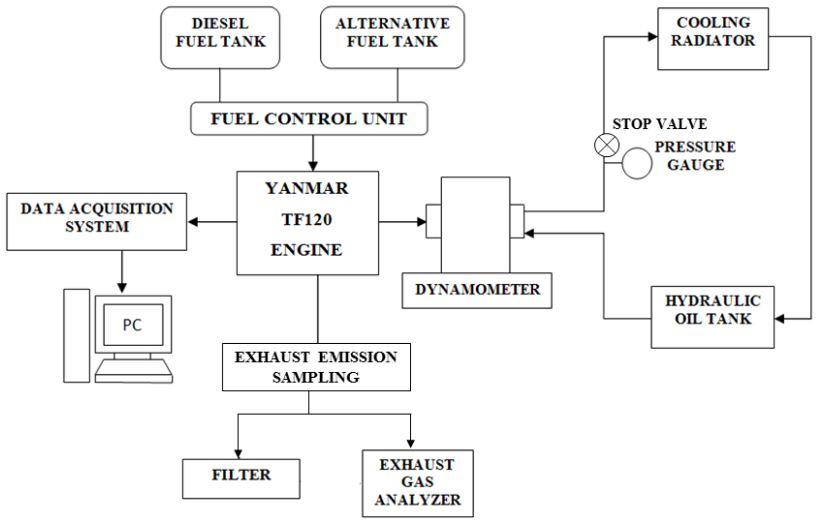

Figure 1: Schematic diagram of the experimental setup

Table 1: Engine specifications

Description	Specification
Engine model	YANMAR TF120
Number of cylinder	1
Bore X Stroke (mm)	92 X 96
Displacement (L)	0.638
Compression ratio	17.7
Continuous output (HP)	10.5 HP at 2400 RPM
Rated output (HP)	12 HP at 2400 RPM

Furthermore, as for the exhaust emission sampling, it was divided in two parts called exhaust gas sampling and particulate matter (PM) sampling. For exhaust gas analysis, gas analyser brand Kane Automotive was used and it was designed to sample and measure the concentration of NOx, CO_2 and O_2. The measurement carried out was synchronised with the engine testing and was analysed using statistical approach. Table 2 tabulated the specifications of the gas analyser. For PM measurement, it was done by taking the mass concentration by passing through a steady flow of diluted exhaust through a filter. The weight difference between before and after sampling was divided by the volume of air pulled through the filter, which then gives the mass concentration of the PM. In order to ensure the accuracy and consistency of the measurement data, the engine had been running for five minutes after changing the fuel. Also, the engine testing was done four times and the average data was taken.

Table 2: Specifications for gas analyzer

Parameter	Resolution	Accuracy	Range
NOx and NO (Electrochemical)	1 ppm	0-4,000 ppm ± 4% or 25 ppm*3 4,000-5,000 ppm ± 6*3	0-5,000 ppm
CO_2 (Infra-red)	0.1%	± 5% of reading *1 ± 0.06% volume*1	0-16% Over-range 20%

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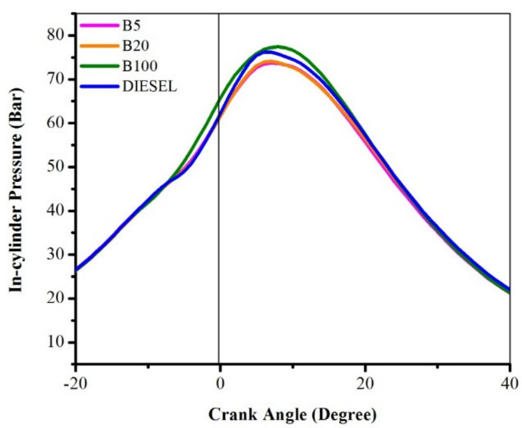
3.0 RESULTS AND DISCUSSION

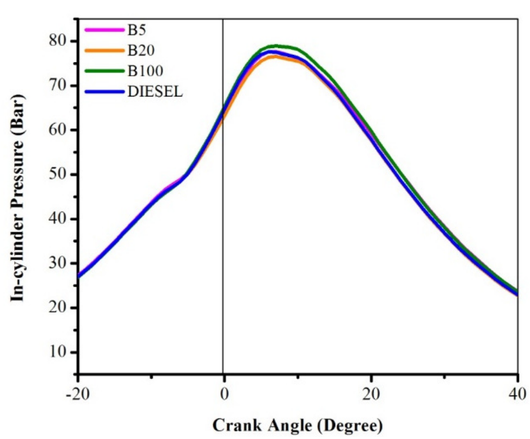
3.1 In-Cylinder Pressure

Pressure variation using different fuel is important in the analysis of performance characteristics. The comparison of in-cylinder pressure between all WCO biodiesel blends (B5, B20 and B100) at an engine speed of 1200 rpm to 2400 rpm are plotted in Figure 2a-e. From this result, overall it shows that as the engine speed increased, the trends of in-cylinder combustion pressure for all test fuels are decreased. Also, it can be seen that lower speed generates higher and more stable combustion pressure compared to other engine speeds. B100 marked the highest in-cylinder pressure of 77.39 bar as compared to other test fuels where B5, B20 and diesel produced 73.71 bar, 74.11 bar and 76.24 bar respectively. Unlike diesel, the viscosity of biodiesel blends are greatly higher and thus causes poor atomization, slower air-fuel mixing and increment of spray penetration. These conditions will bring about a longer ignition delay of biodiesel at the lowest speed and produce higher in-cylinder pressure [10]. The other factors that contribute to the higher peak pressure of B100 is the higher cetane number and higher oxygen content of B100 that leads to an improved combustion process. On the other hand, the in-cylinder pressure for B5 and B20 are closer to diesel due to their closer properties to diesel.

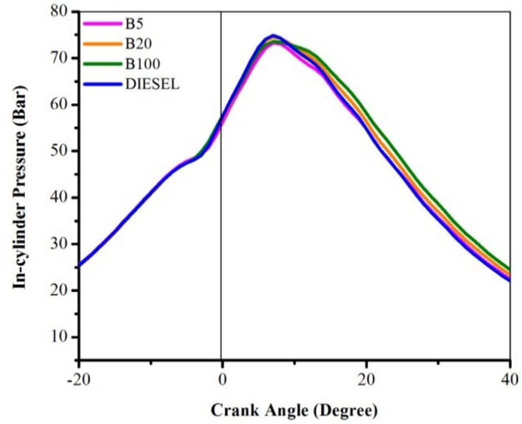
(a) 1200 rpm:



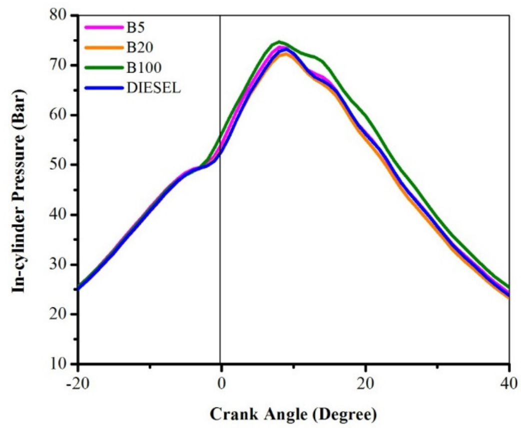
(b) 1500 rpm



(c) 1800 rpm



(d) 2100 rpm



(e) 2400 rpm

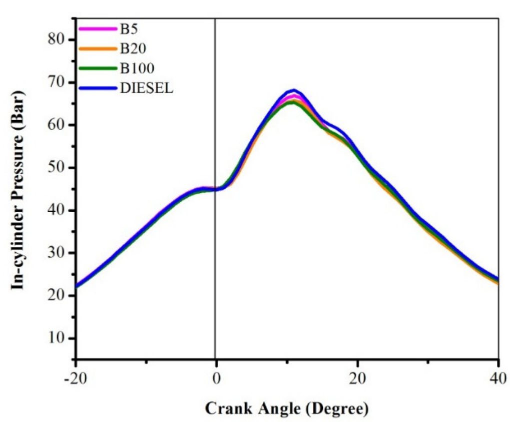


Figure 2: (a) In-cylinder pressure for WCO biodiesel blends (B5, B20 and B100) and diesel at 1200 rpm. **(b)** In-cylinder pressure for WCO biodiesel blends (B5, B20 and B100) and diesel at 1500 rpm. **(c)** In-cylinder pressure for WCO biodiesel blends (B5, B20 and B100) and diesel at 1800 rpm. **(d)** In-cylinder pressure for WCO biodiesel blends (B5, B20 and

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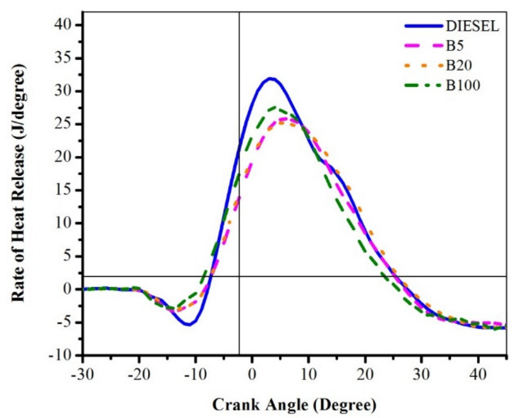
B100) and diesel at 2100 rpm. **(e)** In-cylinder pressure for WCO biodiesel blends (B5, B20 and B100) and diesel at 2400 rpm.

3.2 Rate of Heat Release

In internal combustion engines, the rate of heat release is important in order to determining the start of injection, start of combustion and ignition delay. In addition, it favours the analysis of NOx formation inside the combustion chamber. Figure 3a-b shows the variation of rate of heat release for various test fuels at low engine speed of 1200 rpm and high engine speed of 2400 rpm. This figure shows that all WCO biodiesel blends have identical stages, similar to ordinary diesel. At low engine speed, the rapid mixture burn occurred at -10º crank angle for diesel and -13º for all biodiesel blends B5 WCO, B20 WCO and B100 WCO respectively. This obviously shows that biodiesel blends contributes to an earlier rise in the initial heat release in comparison with diesel. At the same time, this result indicates the agreement with previous results on in-cylinder combustion pressure testing.

(a) 1200 rpm



(b) 2400 rpm

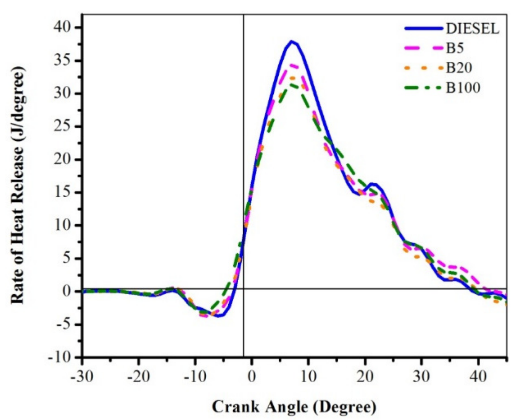


Figure 3 (a) Rate of heat release of WCO biodiesel blends (B5, B20 and B100) and diesel at 1200 rpm. **(b)** Rate of heat release of WCO biodiesel blends (B5, B20 and B100) and diesel at 2400 rpm.

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Furthermore, at high engine speed, it obviously shows the increment of rate of heat release value of all fuels. The location of peak rate of ROHR was also delayed and shifted away from TDC as the engine speed increased. However, due to this longer delay period, more fuel was injected, evaporated and mixed with air which resulted in higher maximum ROHR. From the observations, the higher heat release may be due to the lower temperature burning during late combustion.

3.3 NOx Emission

The comparison of NOx emissions for all of the test fuels at various speeds is shown in Figure 4. Referring to the left side of figure, emissions at low engine speeds of 1200 rpm using diesel produced the lowest level of NOx emissions. Meanwhile, at the same speed of 1200 rpm, the highest level of NOx emission was produced by using the B100 WCO, with an increase of 35.68%. This is due to higher temperatures caused by the improved combustion of B100 WCO as well as the higher oxygen content of B100 WCO [11]. However, when the engine speed increased from 1200 rpm to 2400 rpm, the NOx content produced by B100 WCO had reduced and was lower compared to other tested fuels. Essentially, results of low NOx emissions using a higher biodiesel blend concentration were contrary to results from previous biodiesel studies. Chemical and physical properties of fuel such as cetane number, became a strong link for the reduction of NOx when the cetane number increased. In the case of B100 WCO, the cetane number value of 57.7 was the highest among the other tested fuels. NOx is usually produced during the high temperature combustion process but at the highest engine speed of 2400 rpm the ROHR for B100 WCO was low. On the other hand, B5 WCO and B20 WCO showed that their NOx content was almost similar to that of diesel with just 0.2% to 5.8% difference between them even though the combustion temperature and pressure was lower than diesel. This phenomenon might have happened because of the interesting characteristics of biodiesel such as its structural oxygen content that improved the oxidation of nitrogen and raised the combustion bulk temperature during the combustion period [12].

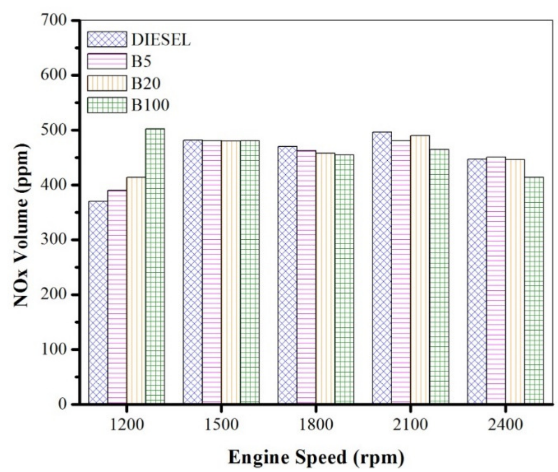

Figure 4 Comparison of NOx content at various engine speeds.

3.4 CO_2 Emission

Figure 5 illustrates the comparison of CO2 content for diesel, B5, B20, and B100 at engine speeds of 1200 rpm to 2400 rpm. The emission of CO2 is one of the main concerns because it is the main component of greenhouse gases contributes to global warming. The figure shows that the CO2 emission for all fuels increased as the engine speed increased. Moreover, at an average speed, which was 1800 rpm, there was an increase of 1.9% to 13.7% for B20 WCO and B100 WCO respectively, as compared to diesel. The increase is agreed upon by most researchers such as Hajbabaei et al. [13] that this condition is due to the average carbon content per energy of the biodiesel, which is implicitly higher compared to diesel fuel. Another reason for the high CO2 emission is due to the oxygen content in biodiesel, which results in a more effective combustion when using biodiesel.

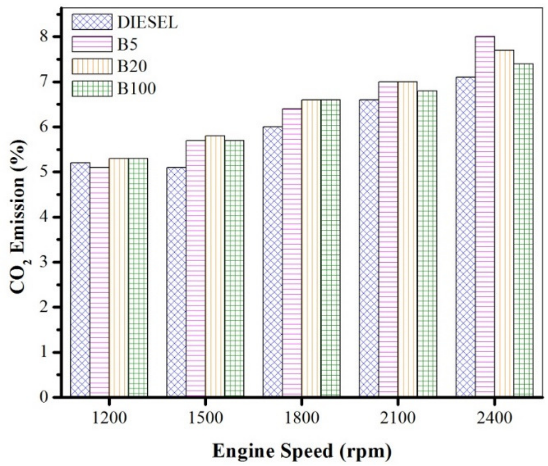

Figure 5 Comparison of CO_2 content at various engine speeds.

3.5 PM Emission

The comparison of PM concentration produced by testing fuels at various engine speeds is shown in Figure 6. Overall, it can be seen that the PM emission for all fuels increased with the increase of engine speed.

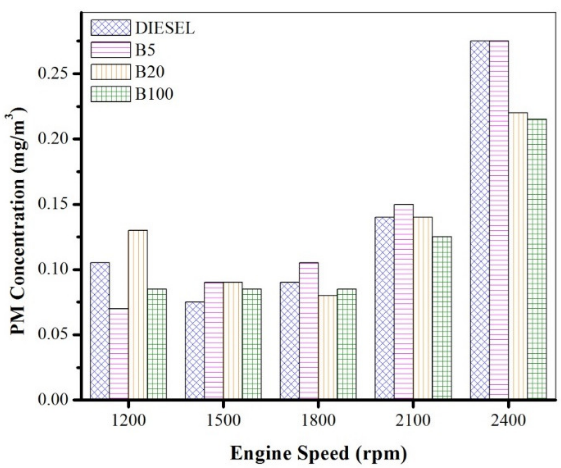

Figure 6 Comparison of PM concentration at various engine speeds

At a moderate engine speed of 1500 rpm to a high speed of 2400 rpm, the B20 and B100 blends showed some improvement in PM control, where they produced lower PM than diesel as well as B5. Compared to diesel, B20 WCO and B100 WCO obviously showed a variance of 20% and 21.8% at an engine speed of 2400 rpm. This is due to the high oxygen content of B100 WCO, which caused a reduction in soot formation and thus enhanced soot oxidation [9].

4.0 CONCLUSION

The in-cylinder combustion pressure and exhaust emission characteristics of diesel and biodiesel blends derived from WCO (B5, B20 and B100) were compared. The experimental results show that the in-cylinder combustion pressure of B5 and B20 were almost similar with diesel, while B100 shows relatively a large difference with diesel due to its properties. For rate of heat release, all biodiesel blends indicated a lower heat release as compared to diesel at both low and high engine speeds. At the same time, for exhaust emissions, B5 showed a close resemblance with diesel and this shows that B5 can be used as a diesel substitute.

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