Impact of diesel-biodiesel-hexanol tri-fuel blends on the combustion and exhaust emissions characteristics of a diesel engine

To cite this article: Zuhaira Abdullah *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **469** 012043

Impact of diesel-biodiesel-hexanol tri-fuel blends on the combustion and exhaust emissions characteristics of a diesel engine

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Abstract. The purpose of this study is to investigate the impact of diesel-biodiesel-hexanol tri-fuel blends on combustion and exhaust emissions characteristics of a diesel engine. The presence of a hexanol ($C_6H_{13}OH$) in tri-fuel blends helps to increase the oxygen content in combustion phase. The experimental tests were performed with YANMAR TF120M single-cylinder, direct-injection diesel engine. The results of tri-fuel blends were investigated and compared with diesel fuel (DF) and neat biodiesel (B100). The engine was run at varying engine loads 0%, 25%, 50%, 75%, and 100% at constant engine speed 1800 rpm. DF and palm oil methyl-ester (POME) were dispersed in 5%, 10%, and 15% hexanol, which were formed as tri-fuel blends. The blending process of tri-fuel blends used ultrasonic emulsifier with cycle 0.5 and an amplitude of 70%, within 2 minutes. Compared to DF, the results reveal the in-cylinder pressure of B100, HE5, HE10, and HE15, were reduced by 2.23%, 1.95%, 2.19%, and 2.00%, respectively at 50% engine load. Furthermore, the heat release rate at 50% engine load for HE15 was increased by 6.42%, gives the highest combustion efficiency. CO, CO_2 and NO_x emissions were decreased by 7.06%, 12.20%, and 22.85% for HE15 at 75% engine load. This study concluded that HE15 fuel blend shows positive impacts in combustion and emissions characteristics of a diesel engine.

1. Introduction

The diesel engine is the main source of propulsion energy used domestically for automobile transportation, heavy industry and agriculture machinery [1, 2]. In addition, the diesel engine is well known for its effective rigid structure and its high performance in the combustion phase. High torque, high efficiency and robustness are also advantages for the diesel engine. However, the diesel engine most commonly known as a major pollutant contributor such as carbon dioxide (CO_2) emission is one of the greenhouse gas effects that damage the ozone layer emitted by diesel engine [3]. Moreover, nitrogen oxide (NO_x) emitted by a diesel engine contribute to the production of acid rain, which causes harmful effects on humans, plants, animals and even in infrastructure. Also, diesel fuel (DF) produced from fossil fuels, would have predicted in 2070 that the world's fossil fuel reservoir would be depleted. Therefore, the world will face great problems of limiting fossil fuels to produce diesel fuel due to it is non-renewable and cannot be reused.

Excessive emissions leading to pollution and natural disasters are one of the main contributors to the diesel engine. To address the issues, researchers around the world continue to seek new strategies and ideas to increase combustion efficiency and reduce exhaust emissions characteristics [4]. Researchers used various methods to reduce exhaust emission, while at the same time, maintaining the diesel engine's energy efficiency [5]. Among the strategy explored by many researchers, diesel engine can be operated and combust with alternative fuels [6, 7]. There are many additive for fuels was added into DF, such as nanoparticles, Tween-Span (emulsion), germanium, and higher alcohols to formed as alternative fuels [8-10]. Biodiesel is one of the alternative fuels that has potential to minimize the problems posed due to its renewability, biodegradability and better fuel properties [11, 12].

The term 'biodiesel' refers to the methyl ester of long-chain fatty acids derived from animal fats, plants and vegetable oils undergoing a trans-esterification process. Examples of biodiesel are waste cooking oil, jatropha fuel, *Calophyllum inophyllum* (CI), and palm oil, which have a high potential to replace the usage of DF. Nadir Yilmaz et al. [13] reported that waste cooking oil was used as biodiesel to synthesize the effect of waste cooking oil-butanol fuel blends on 10% and 20% of butanol in performances and emissions characteristics. The authors showed that the BSFC was reduced by 7.5% and 6.25% for 10% and 20% butanol compared to biodiesel. In this case, biodiesel (waste cooking oil) has low calorific value and high density, by 40.5MJ/kg and 0.855kg/m^3 respectively compared to DF. Jatropha fuel-biodiesel-diesel fuel blends were studied by Mehta et al.[14] showed that BSFC was increased in the range of 4.9%-10.7% compared to DF. Exhaust gas emission showed a significant decrease CO by 42% compared to DF. However, NO_x showed an average increase of 2.4%-11% compared to DF. Palm oil methyl ester is chosen as a substitute for diesel fuel due to it has potential to reduce emission generated. Palm oil undergoes methyl trans-esterification method to form as a palm oil methyl-ester (POME). The advantages of palm oil are low cost and high productivity in term of availability, while reducing emissions, improving combustion efficiency of performance. Furthermore, palm oil is readily available as a raw material for biodiesel production due to renewable, huge quantities and high oil content. Palm oil has very similar properties to diesel fuel as sulphur content, flash point, cetane number, aromatic content and biodegradability are concerned [15]. Palm oil has great potential to become a biodiesel blend with DF and long-chain alcohol (hexanol) formed as a tri-fuel blends.

Alcohol divided into two categories, which are short-chain alcohol and long-chain alcohol. The carbon atom(s) with less than five carbon atoms are known as short-chain alcohol such as methanol, ethanol and propanol. While carbon atoms with more than five carbon atoms are known as long-chain alcohol known for it's as an oxygenated liquid properties, which could increase the oxygen content thus, performing better combustion and reduces exhaust emission. Higher alcohol-biodiesel-diesel blends were carried out by Imdadul et al. [16] on a light-duty diesel engine and showed that the increasing proportion of pentanol in biodiesel reduced the kinematic viscosity and density by an average of 2.4% and 3.1%, respectively compared to (Calophyllum inophyllum) CI20. Conversely, authors also indicated to BSFC and BTE, with BSFC decreasing by an average of 8.7% and BTE increase by 15%. This is because the lower density and viscosity value by 0.837kg/m^3 and 3.64 mm^2/s receptively, and higher ignition efficiency will increase the oxygen content.

Most of the studies were conducted in different biodiesel with different alcohol types. None of researchers focused on the low volume ratio of POME and hexanol. A previous study of diesel-waste cooking oil methyl ester was done by Muralidhran et al. [17] tested of 20%, 40%, 60% and 80% used waste cooking oil methyl ester as biodiesel. The results show that the NO_x emission was increased from 621ppm to 640ppm for B40 at compression ratio 21 due to high peak pressure occurred. Moreover, just a few of researchers that investigated about palm oil, the rest of them, only focus on, jatropha oil, waste cooking oil, jojoba oil and others vegetable oil [18, 19]. Senthil Kumar et al. [20] investigated an experimental use of methanol and jatropha oil in an internal combustion engine with 30% by volume ratio of jatropha oil. Result states that smoke was reduced from 4.4 to 4.1BSU due to good atomization of the fuel. Since none of them conducts experiments with low volume ratio and 100% pure biodiesel POME, unless biodiesel that mixes with DF or others oil. In order to fill up the gap, these studies on POME (B100) and DF were added for 5%, 10% and 15% of hexanol concentration to produced tri-fuel blends. In this experiment an unmodified YANMAR TF120M single-cylinder, direct injection diesel engine was used. Further investigations are necessary to evaluate an impacts of diesel-biodiesel-hexanol tri-fuel blends on combustion and exhaust emissions characteristics of a diesel engine were measured at constant engine speed 1800 rpm and various engine loads 0%, 25%, 50%, 75% and 100% for DF, B100, HE5, HE10 and HE15.

2. Experimental setup and test procedure

2.1 Preparation of test fuels

The tri-fuel blends consisted of pure diesel, pure biodiesel and long-chain alcohol. A standard fuel DF JIS #2 provides the pure diesel (Japanese Industrial Standard), which used as a base fuel. Biodiesel is representative by Palm Oil Methyl Ester (POME) or known as biodiesel B100 by FCV Biotechnologies SDN BHD Gebeng, Kuantan. While, 2-ethyl 1-hexanol with 99% purity of alcohol brought from brand Acros Organics. The tri-fuel blends ratio were prepared with a constant 10% of POME, various volume concentrations by 5%, 10% and 15% hexanol illustrated in Table 1. In order to stabilize and completely dissolve between diesel, POME and hexanol, 70% amplitude ultrasonic emulsifier (Hielscher UP400S) used 0.5 cycles within 2 minutes to mix well the tri-fuel blends. Mixing process should take no longer than 2 minutes to avoid harmful chemical properties and the element itself. The temperature was kept between 30°C - 32°C to maintain the chemical properties and prevent damage to the hexanol element. No additive was added to avoid phase separation. The procedure was repeated until 6 liters of fuel blends were obtained for the engine test.

Table 1. Tri-fuel blends ratio

Fuel test	Types of solution
DF	100% diesel fuel
B100	100% palm oil methyl ester (POME)
HE5	85% diesel fuel + 10% POME + 5% hexanol
HE10	80% diesel fuel + 10% POME + 10% hexanol
HE15	75% diesel fuel + 10% POME + 15% hexanol

2.2 Test engine and facilities

In this experiment, a YANMAR TF120M single-cylinder direct-injection diesel engine was used. The diesel engine is a water cooled direct injection that occurs at 17° CA before Top Dead Center (bTDC). The specification of the diesel engine details shown in Table 2. As shown in Figure 1, the schematic diagram of the test engine with necessary that connecting with dynamometer equipment. The dynamometer used in this experiment was an eddy current dynamometer model BD 15kW by Focus Applied Technology with SAE J1349 Standard Engine Power Test Code for a diesel engine. In addition, the dynamometer was mounted on the spherical bearing and fitted directly on the diesel engine. The engine setup was completed with a SIRIUS i-HS Data Acquisition Device (DAQ) by DEWESOFTX2 engineering software was connected to a fiber optic transducer, type OPTRAND C82294-Q pressure sensor to measure combustion performance data. Despite, to measure the exhaust emissions used Automotive Emission Analyzer (QROTECH) for collecting the data of CO, CO_2 and NO_x. The engine testing were repeated three times for each fuel.

Table 2. Engine specification

	Specification
Engine type	YANMAR TF120M
Number of cylinder	1
Bore x stroke	92 x 96 mm
Displacement	0.638 L
Compression ratio	17.7
Injection timing	17^o bTDC
Continuous output	10.5 HP at 2400 rpm
Rated output	12 HP at 2400 rpm
Cooling system	Water cooled

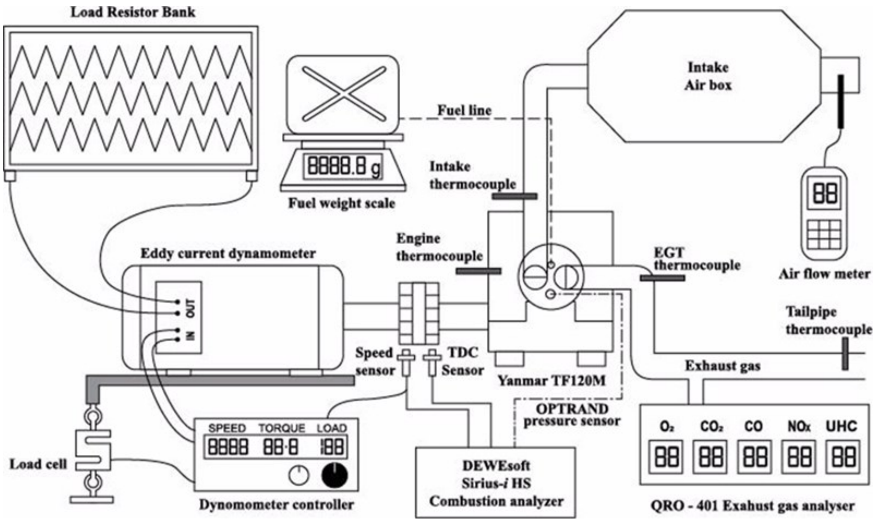


Figure 1. Schematic diagram of experimental setup for single cylinder diesel engine

2.3 Test engine and instrumentation

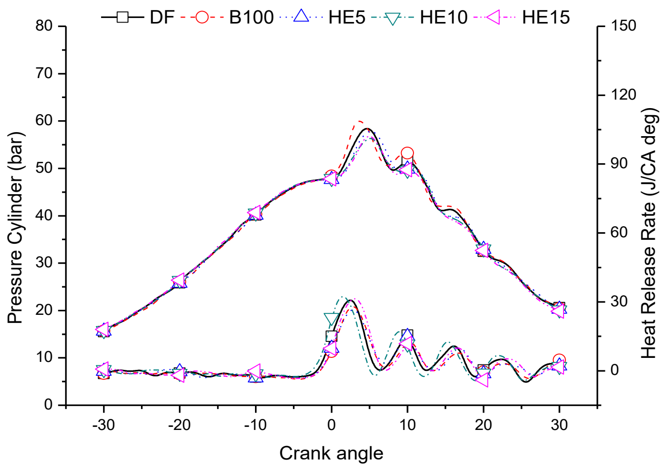
The engine tests were carried out five engine loads, which operate in low range engine load from 0%-25%, medium engine load 50%, and high range engine load of 75%-100%. These engine loads correspond to 0 Nm, 7 Nm, 14 Nm, 21 Nm, and 28 Nm at a constant engine speed of 1800 rpm. The data recorded for all fuel tests, were repeated three times to ensure the data collected was accurate and validated. Before starting the experiment, the engine diesel must be warm up with DF for 10 minutes to stabilize the fuel blends operating system. The diesel engine must be flushed with DF at each test to anticipate the waste fuel blends.

3. Results and discussion

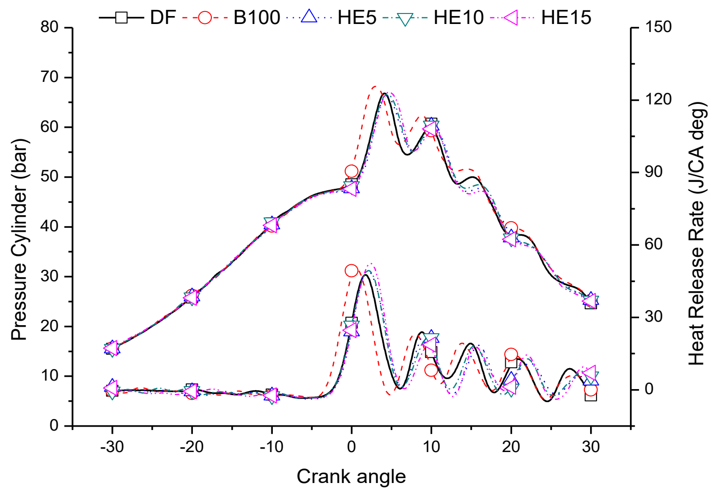
3.1 Combustion characteristics – combustion pressure and heat release rate curve

In overall observation, the in-cylinder pressure and the heat release rate were reported, with the comparison between DF, B100, HE5, HE10 and HE15 being plotted against crank angle (CA). Figure 2 shows the characteristics for in-cylinder pressure and heat release rate curve between test fuels at constant engine speed 1800 rpm for varied engine loads 0%, 50% and 100%. Ignition delay was obtained from the start of fuel injection (SOI) to the start of combustion (SOC). Figure 2 (a) illustrated that the in-cylinder has a peak pressure at 3°CA for all test fuels at low engine load 0%. Referring to the graph, in-cylinder pressure test fuels was reduced by 3.11%, 4.47%, and 6.30% for HE5, HE10, and HE15, respectively, compared to DF. Meanwhile, B100 has been increased by 8.56% compared to DF. This is because of the pure POME, B100 consists of a high density and kinematic viscosity of 0.864 kg/m3 and 4.50mm2/s which is results of high premixed combustion [21]. Apart from that, an increased of the fuel-air mixture during the ignition delay leads to good fuel atomization due to the small size of droplets. Figure 2 (b) demonstrates 50% engine load, showing in-cylinder pressure results decreased by 2.23%, 1.95%, 2.19% and 2.00% for B100, HE5, HE10 and HE15. The reduction has shifted further away from 3°CA to 4°CA, the fuel-air mixture has decreased during ignition delay leading to poor fuel atomization in the complete combustion phase. In addition, Figure 2 (c) shows that at high engine load 100%, B100, HE5, HE10 and HE15 were reduced by 6.14%, 1.99%, 1.38%, and 0.002% compared to DF. The results can be explained by the presence of hexanol enriched in an oxygen content carrying a strong premixed combustion phase. Moreover, the ignition delay, which was shorter at high engine load due to the amount of fuel burned in the combustion chamber, was released in a large amount of power output. Regarding to the results, a work by Melvin et al. [22] has shown a reduction in-cylinder pressure of 13.8% for 10% EGR as combustion progresses over the expansion stroke, leading to a drop in peak pressure and heat losses. Furthermore, the overall graph shows the increase in engine load, increasing the peak pressure as 58.21 bar, 68.33 bar, and 72.02 bar for 0%, 25%, and 100% engine loads. Referring to the results, the efficiency combustion due to the combustion that occurred at peak pressure was observed.

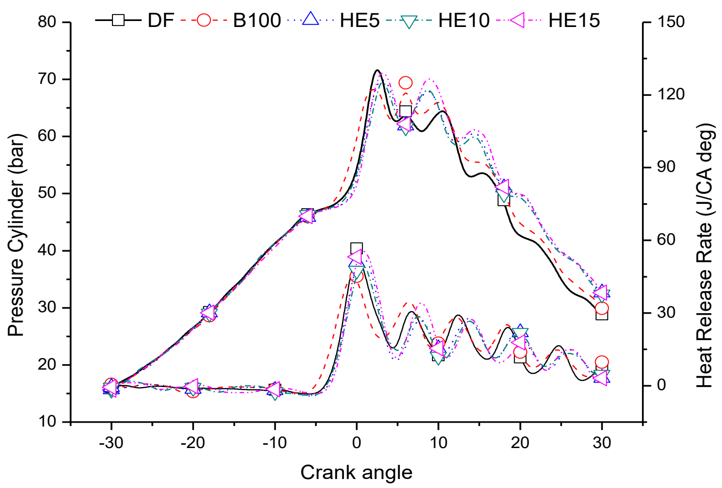
Figure 2(a) – (c) shows the heat release rate (HRR) curve between DF, B100, HE5, HE10, and HE15 at constant engine speed 1800 rpm for different engine loads 0%, 50%, and 100%. The crank angle refers to 4°CA for 0% engine load as shown in the Figure 2(a) results of HRR decreased by 6.28%, 10.84%, and 7.03% for HE5, HE10, and HE15, respectively, compared to DF. The ignition delay of fuel is slightly longer than B100, due to the presence of oxygen content in the tri-fuel blends. The higher oxygen content leads increased HRR as more fuels required to rapidly combust during longer ignition delay [23]. Figure 2(b) shows the HRR of 50% engine load increase by 3.4%, 2.48%, and 6.42% for HE5, HE10, and HE15, respectively, compared to DF. The maximum increase of HRR for HE15 is 6.42%, due to the fact of more additional hexanol that enriched the oxygen content. Furthermore. The increases of HRR of fuel blends, due to the increases spray characteristics by addition of hexanol. Moreover, the variation of HRR on 100% engine load shown in Figure 2(c) showing DF were reduced by 10.07%, 16.16%, and 6.21%, respectively, as HE5, HE10 and HE15. The longer ignition delay at high load due to the HE15 spray has more time for confusion with the surrounding air, which is mainly composed of HRR due to premixed combustion. This is because the fuel spray has more time to mix with the ambient air. Given the additive of hexanol into the fuel, during the time of atomization, the in-cylinder temperature decreased due to the high latent heat of evaporation. Regarding to the reduction, combustion that occurred in a low temperature will produced low HRR and reduced peak pressure cylinder [24].



a) Combustion pressure and HRR against CA for engine load 0%



b) Combustion pressure and HRR against CA for engine load 50%



c) Combustion pressure and HRR against CA for engine load 100%

Figure 2. Combustion pressure and heat release rate in varies engine load of DF and fuel blends at a constant engine speed of 1800 rpm.

3.2 Exhaust gas emissions measurements

The variation of exhaust emission contents of carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxide (NO_x) was measured using the QROTECH gas analyser. The graph was plotted between test fuels against engine loads at constant engine speed 1800 rpm.

3.2.1 Carbon monoxide emissions.

Biodiesel fuel can be considered as environmental-friendly, but zero emission cannot yet be achieved. The formation of CO due to incomplete combustion of fuel and the effect the combustion will be slow in burning process, thus elongated the ignition delay. The CO formation for test fuels shown in Figure 3 increases as the engine load increase. Referring to the graph, it was observed that 75% and 100% of the engine load increase by 13.03% and 36.92% for HE10. In addition, the highest difference occurred at 100% of engine load that was increase the CO emission by 43.41% for HE5. Suhaimi et al [25] found that the highest latent heat vaporization occurred during the increases in-cylinder temperature found the same result. In addition, tri-fuel blends yield higher CO emission than conventional diesel, because the combustion temperature is lower and have a quenching, lean flame zone. However, HE15 has improved successfully due to the reduction of CO emission by 7.06% with 75% engine load. The reduction of HE15 is due to the highest oxygen content of hexanol and it becomes good vaporization, lead to complete combustion, thus reducing CO emission. Moreover, the micro-explosion process where the secondary atomization explodes from fuel to the fine fuel droplets that improving the air-fuel mixture. Furthermore, the greater surface area in the combustion of fuel is takes time to completely burn off the carbon, resulting in a shorter overall flame length and decline the possibility of flame hitting the engine fuel wall.

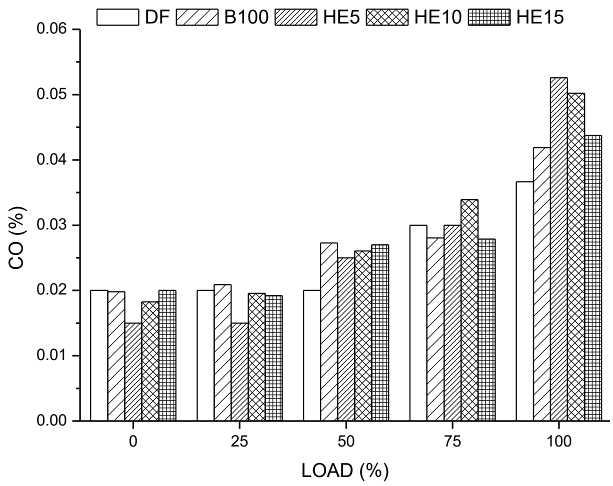


Figure 3. Variation of CO emission for diesel fuel and fuel blends

3.2.2 Carbon dioxide.

The emission of CO_2 is the main product of exhaust emission is an indicated to complete combustion inside the combustion chamber. The presence of CO_2 emission was produced with accessible oxygen, where the hydroxyl radical (OH) is one of primary oxidizing agents that convert CO to CO_2. In general, the graph shows the formation of CO_2 decreased in each load of the engine. In Figure 4 shows, the formation of CO_2 gradually decreased by 1.66%, 8.02%, 13.23% and 11.35% according to B100, HE5, HE10 and HE15 compared to DF at 100% engine load. Oxygenated fuels are combusted more efficiently to a high engine load compared to a low engine load [17]. Other than that, reasons for the higher amount of oxygen atoms in the tri-fuel blends formed from hexanol as oxygenated agent. However, the maximum reduction of HE5 can be seen with an engine load of 75% and reduction of 30.54%. This is because, the transformation of CO onto CO_2 could affect the formation of the CO_2 decrease due to the present of oxygen that effect of combustion temperature and the high amount of OH radical. Ileri et al [26] reported that the reduction of CO_2 emission is due to the increase of oxygen and hydrogen molecules in the fuel structure. In addition, Machacon et al. [27] concluded that the higher latent heat of vaporization of the long-chain alcohol that caused the lower combustion temperature thus reduced the CO_2 emission.

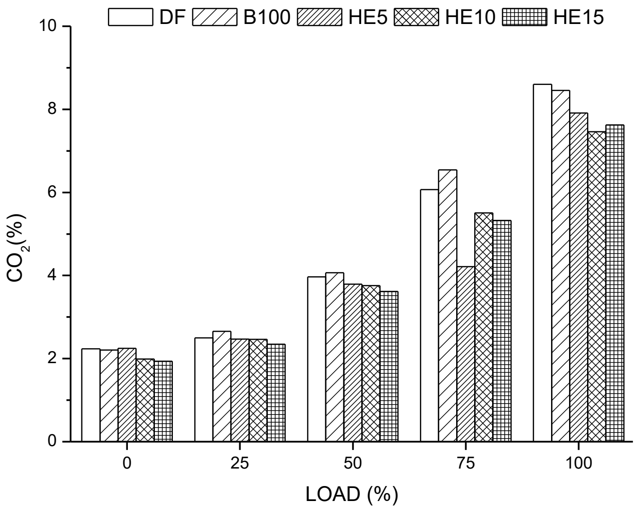


Figure 4: Comparisons of CO2 emission for diesel fuel and fuel blends

3.2.3 Nitrogen oxide emission.

The tri-fuel blends can be used as a complete replacement in diesel engine, thus increase combustion temperature results in higher NO_x emissions and occupy the first place in part of exhaust emission. This is because the effect of NO_x will be detrimental to human life. NO_x is a product of a nitrogen containing fuel, excess oxygen, and excessively high combustion gas temperature [28]. The NO_x emission presented in Figure 5. shows the tendency of the general graph when the engine load increases, the NO_x emission also increases for all tri-fuel blends. At low engine load, 0% was reduced by 4.63% in the average all fuel test HE5, HE10 and HE15 compared to B100. Meanwhile, at high engine load, 100% improved the reduction by 6.76%, 15.82%, 19.36%, and 25.33% for B100, HE5, HE10, and HE15, respectively, compared to DF. The formation of NOx occurred at a higher gas temperature in-cylinder and has a high oxygen content compared to DF. Two factors affect the NO_x emission, which is that tri-fuel blends have a highly latent heat of vaporization, which leads to a lower combustion temperature, thus reduces NO_x formation. Second, the longer ignition delay will be applied to the fraction of the burned fuel increase in the premixed region and the NO_x emission formation will increase. Li et al. [29] also obtained that NO_x reduction by 9% for diesel-biodiesel-pentanol. Under high load conditions, element nitrogen oxidation occurs to NO. The NO compound is combined with O_2 that comes from long-chain alcohol to create nitrogen dioxide NO_2. Vaporization of hexanol as reduces the temperature of the flame and changes the chemical compositions, resulting in a higher concentration of OH radical during the combustion of tri-fuel blends. The increases in NO_x emission due to combustion initiated by pilot injection can accelerate the combustion process, resulting in a higher flame temperature.

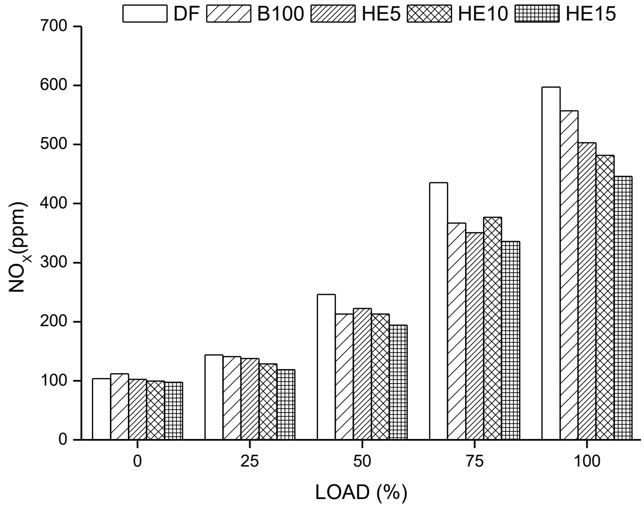


Figure 5. NOx emission versus engine load for diesel fuel and fuel blends

4. Conclusions

The impact of diesel-biodiesel-hexanol tri-fuel blends on the combustion and exhaust emissions characteristics of a diesel engine has been investigated. The test fuels were compared and observed for DF, B100, HE5, HE10, and HE15 under various engine loads at constant engine speed 1800 rpm. The results of the experiment were summarized as follows:

- The maximum reduction in-cylinder pressure occurred at 3°CA for HE15 by 6.30% at 0% engine load due to the presence of hexanol enriched oxygen content leading to a strong premixed combustion phase.
- The HRR increased by 6.42% with engine load 100%, which indicates a better air-fuel mixing process and a larger fraction in tri-fuel blends.
- The most efficient reduction in CO emission at 75% engine load was reduced by 7.06% for HE15 due to high oxygen content and good vaporization.
- Improves the replacement of POME and hexanol in DF, decreasing the NO_x emission by 25.33% for HE15 with at 100% engine load.

Acknowledgement

The authors are thankful to the Power Engine Lab, Faculty of Mechanical Engineering University Malaysia Pahang for providing diesel engine and financial support given under PGRS170357.

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