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Research paper

Combustion Characteristics of a Direct Injection Diesel Engine Fueled with Diesel-Ethanol-Palm Oil Methyl Ester Blends

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Abstract

In this study, three different diesel-ethanol–palm oil methyl ester (PME) blends were used as fuel to investigate the combustion characteristics and engine emissions at the maximum engine speed of 1600 RPM. The characteristics were simulated by using Converge CFD software for a Yanmar single-cylinder direct-injection diesel engine parameter. 10%-40% of PME and 10%-40% ethanol were added to 50% diesel to make 100% blends and the results were compared to the combustion characteristics of 100% diesel fuel. The results indicated that the combustion characteristics of diesel-ethanol–PME blends have changed; a high percentage of ethanol have longer ignition delay and shortened with PME addition; a high percentage of PME in diesel-ethanol blends increased the in-cylinder pressure and heat release rate of the engine. Overall, compared to 100% diesel fuel, the diesel-ethanol-PME blends could lead to a reduction of both NOx and particulate emissions of the diesel engine except for the result of 40% of PME blends that has slightly higher NOx emission compared to diesel. With a high percentage of PME (E10B40) in the blends, the HC, CO emissions could decrease but slightly increase the NOx. Therefore, the implementation of PME in diesel-ethanol blends leads to better engine combustion and reduced the greenhouse emission from the engine.

Keywords: *Biodiesel, Emission, Ethanol, Heat release rate, Ignition delay.*

1. Introduction

The potential of diesel engine is well known for its high engine performance in heavy-duty industries, which helps the economic growth of many transportation industries [1]. The implementation of biofuels in replacing fossil fuel will result in reducing the fossil fuel dependence, reduced the greenhouse emission and increase the agriculture economic contribution. Based on the 10th Malaysia plan, Malaysia is set to be transformed into a developed nation by focusing on 12 National Key Economic Areas (NKEAs) where palm oil is highlighted as one of the significant contributors to Malaysia's economic growth. Transforming palm oil into biofuels was one of the eight entry projects that have been proposed by commercializing the second generation biofuel as well as to improve the sustainable value-added activities in automotive industries [2].

Palm oil methyl ester (PME) and ethanol are made from edible bio-source products and are believed to reduce the greenhouse gas emission and increase the dependence on energy [3-4]. Palm oil was the largest feedstock and the biggest economic contributor to Malaysia [5]. Palm oil can be easily converted into biodiesel through transesterification process and change the fuel properties and allow the fuel to be used in a diesel engine without modification [6]. The transesterification process enables the tri-glycerides that contain a very long carbon chain to have better fuel density and viscosity [7]. Mixing palm oil without transesterification process can cause injector choking and fuel deposition on the engine injection system due to the high viscosity of the fuel [8].

Ethanol, with its high oxygen contents, and low viscosity can slightly reduce the viscosity of the diesel-PME blends [9]. However, lower cetane number and high water contents of ethanol may reduce the engine performance and leads to engine corrosion problem [10-11]. Meanwhile, PME has a very high cetane number, high oxygen contents (10% - 15% by weight) and is able to act as a lubricant for the engine [12-13]. These properties result in a reduction of harmful exhaust emission such as HC, CO, CO2 and particulate matter [14]. Therefore, diesel-ethanol-PME blends are the perfect fuel combination to increase the engine efficiency, reduce engine emission and to act as a lubricant in the engine.

In compression ignition engine, ignition characteristics are very important as an indicator of the combustion quality. Ignition delay has been considered as the most important parameter in compression ignition engine. Ignition delay is defined as the time interval between the start of injection and the start of ignition when the fuels are reacted with air in the combustion chamber [15-16]. Ignition delay is dependent on physical properties and chemical properties such as density, viscosity, combustion chamber temperature and pressure. Ignition delay can be easily identified from the pressure and heat release rate (HRR) profile when the pressure-time or

HRR-time curve rapidly changes or separate from the motoring curve [17]. Ignition delay gives a very big influence on the engine performance because shorter ignition delay will have a longer combustion duration to allow all the fuel to atomize, mix with air and completely burn [18]. Blending PMEin diesel was tended to achieve higher peak pressure compared to diesel and influence many combustion parameters [19]. This is because biodiesel is an oxygenated fuel that has a high cetane number and possesses a shorter ignition delay [20].

Blending biodiesel in diesel results in lower CO, and HC emissions due to higher oxygen contents of the biodiesel [13]. Higher oxygen contents of fuel in combustion are able to provide enough oxygen and helps to burn all the fuels. However, high oxygen contents of fuel during combustion increases the peak temperature and leads to higher NOx emission. High NOx emission indicates a better combustion for the engine due to oxygen contents. Furthermore, high NOx emission also affected by the mechanism and unsaturation level of a biofuel [21]. A fuel with a higher heat release rate at early combustion and decreased in the late combustion phase can increase the emission of NOx [5].

The objective of this paper is to investigate the ignition characteristics of diesel-ethanol-PME blends involving ignition delay, pressure and heat release rate during combustion. This paper also aims to study the emission reductions of the engine from the implementation of ethanol and PME in diesel fuel. In this research, a simulation work was conducted using CONVERGE CFD software based on Yanmar TF90 single-cylinder diesel engine parameter for three compositions of diesel-ethanol-PME operated at 1600 RPM in comparison with diesel fuel.

2. Methodology

2.1. Fuel composition and properties

Three types of fuel were blended using diesel (nC7H16), ethanol (C2H5OH) and PME (C16H34O2). The three blends used were 40% ethanol, 10% PME (E40B10), 25% ethanol, 25% PME (E25B25) and 10% ethanol, 40% PME (E10B40) and were mixed with 50% diesel fuel. Fuel properties of diesel and ethanol were obtained from CONVERGE CFD software databank including density, viscosity, the heat of vaporization, thermal conductivity, vapour pressure and specific heat capacity from 0 K to its critical temperature.

CONVERGE CFD software is a computational fluid dynamic software that has specially designed for engine combustion application that has the ability to have auto meshing generation with the AMR (Auto Mesh Refinement) to improve the analysis accuracy. A grid independence test was conducted to select a grid size for the accuracy prediction by selecting AMR to have the finest meshing. The grid size of 0.004 m was chosen since it has the most convenient to be used with smallest error percentage around 4.02%. Thermo-physical properties of diesel, ethanol and PME were shown in Table 1. The fuels were blended before they were injected into the combustion chamber through a 4-hole nozzle injector. A proper mixing method can avoid the separation between diesel and ethanol phase due to their immiscibility.

2.1. Simulation setup

In the simulation setup, all the fuel thermo-physical properties were used as inputs. These properties are very important simulation parameters to make sure the combustion will occur in the suitable condition of the fuel. Besides, a suitable chemical reaction data need to be generated. Since PME has very large mechanism reaction, a mechanism reduction process was conducted earlier to reduce the unwanted species in order to have a better fuel reaction mechanism that would be compatible with the simulation software. The species for the mechanism reduction were chosen by identifying the least important species based on the chemical reactions of Methyl Decanoate, Methyl Butanoate and N-heptane [22]. This reduction was performed by using mechanism reduction module provided in CONVERGE CFD software.

Table 1: Thermo-physical properties of diesel, ethanol and PME

Properties	Diesel	Ethanol	Palm oil methyl ester (PME)
Critical temperature (K)	540.3	513.9	780
Density (kg/m^3)	683.75	789.37	888
Viscosity (N.s/m^2)	1.22×10^{-6} - 3.77×10^{-3}	4.04×10^{-5} - 6.0×10^{-3}	7.75×10^{-3}
Liquid surface tension (N/m)	1.0×10^{-5} - 2.54×10^{-2}	4.1×10^{-4} - 2.44×10^{-2}	3.7×10^{-2}
Heat of vaporization (kJ/kg)	106 - 486	369 - 13000	459
Vapor pressure (MPa)	0 - 3.03	0 - 6.55	0
Specific heat capacity (J/kg.K)	2020 - 3845	2230 - 6812	2020
Thermal conductivity (W/m.K)	0.06379 - 0.156	0.11179 - 0.1865	0.0661

The injection shape rate and fuel composition ratio were specified in the injection model by identifying the injection pressure, discharge coefficient, nozzle diameter and engine speed. Hence, the shape rate of fuel was generated from a virtual injection rate generator created by Universitat Politecnica de Valencia [23], where the nozzle hole diameter of the injector is 0.22 mm, injection pressure is 19.613 MPa and discharge coefficient is 0.6088.8.

CONVERGE CFD software is used to study the combustion and emission characteristics which were analyzed by the software for the multi-fuel components based on the Yanmar TF90 single-cylinder diesel engine parameter. A combustion chamber model is prepared based on the engine parameter as shown in Figure 1. Table 2 shows the simulation setup and engine specification that has been used in this simulation. The simulations were conducted on three different fuel compositions, namely E40B10, E25B25 and E10B40 at 1600 RPM.

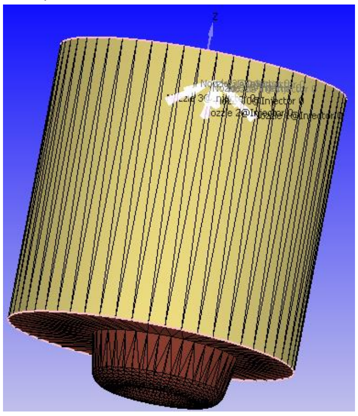


Fig. 1: Yanmar TF90 single cylinder diesel engine model

Table 2: Engine specification and simulation parameter [24]

	Engine specification
Model	Yanmar TF90
Bore x stroke	0.085 m x 0.087 m
Connecting rod length	0.13 m
Compression ratio	18
Injection timing	-18 ˚CA BTDC
Injection pressure	200 bar
Injection duration	10 ˚CA
Nozzle diameter	0.22 mm
Intake valve open (IVO)	-168˚CA BTDC
Exhaust valve closed (EVC)	138˚CA ATDC

This simulation also was conducted on 100% diesel fuel in comparison to the blends. This simulation was a close system simulation which involves only the combustion process started from intake valve close (IVC) at -168°CA BTDC and ended before exhaust valve open (EVO) at 138°CA ATDC. Combustion characteristics of the blends such as pressure, heat release rate and ignition delay were studied. In CONVERGE CFD software, the in-cylinder pressure and temperature displayed in therm.out data represent the average of pressure and temperature in the cylinder. The output files of the simulation are generated by mixing the related output of the three fuels. Emissions of NOx, CO2 and HC also were determined for all fuel blends.

3. Results and Discussion

3.1. Combustion characteristics

Figure 2 shows the in-cylinder pressure and heat release rate (HRR) profile of the composition of the blend of E40B10, E25B25 and E10B40 for one close cycle. HRR is closely related to the in-cylinder pressure that obtained through-out the simulation. CONVERGE software are able to determine the HRR from the mathematical formula as shown in equation 1 where γ is the ratio of specific heat capacity at constant volume to the at constant pressure.

$$\frac{dQ}{d\theta} = P\frac{\gamma}{\gamma-1}\frac{dV}{d\theta} + V\frac{1}{\gamma-1}\frac{dP}{d\theta} \quad (1)$$

The variation of peak in-cylinder pressure for diesel-ethanol–PME blends shows that the in-cylinder pressure was depending on the fuel fraction. When compared to diesel fuel combustion, the peak pressure of all blends was lower than diesel fuel. As observed from the graph, E10B40 with the highest percentage of PME resulting higher in-cylinder pressure compare to the other blends. This is because PME has a higher heating value and cetane number that influenced the blends to have higher in-cylinder pressure. Meanwhile, blends with higher ethanol percentage show lower in-cylinder pressure and the peak pressure of these blends were away from the top dead centre (TDC). The peak pressure results were compared toTse et al. where 20% ethanol in diesel-biodiesel blends has lower peak pressure [12]. This proved that E10B40 that contains highest PME percentage have higher peak pressure.
The graph in figure 2 shows that a higher percentage of PME blend result in higher HRR compared to other blends. However, E10B40 that contains 40% of PME produce slightly lower HRR compared to diesel.

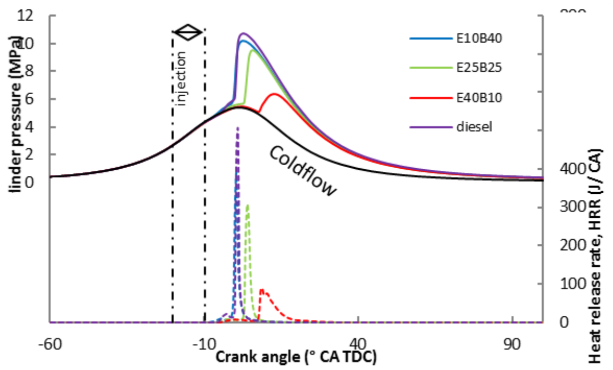


Fig. 2: In-cylinder pressure and heat release rate (HRR) profile of diesel-ethanol-PME blends at 1600 RPM engine speed.

Diesel fuel may have a longer ignition delay, however, the accumulation of fuel during the delay is increased and increase the HRR of diesel higher than E10B40. Upon injection at -18°CA TDC, the HRR of all blends started to rapidly increase. E10B40 and diesel fuel show the sharpest HRR peak compared to other blends. This is because the premixed combustion of PME is less intense due to the shorter ignition delay. Since the combustion of E10B40 has very high HRR peak, it is really difficult to differentiate between the premixed combustion peak and diffusion combustion peak. Meanwhile, E25B25 and E40B10 blends show lower HRR and heat release of these blends occur later than diesel due to lower heating value and cetane number of ethanol.
Start of ignition was observed by identifying the rapid changes of pressure or HRR. The start of ignition of the blends with a higher percentage of PME have shorter ignition delay and the blends with a higher percentage of ethanol have a very long ignition delay. This is because PME has a higher cetane number that able to shorten the ignition delay and allow the fuel to combust as soon as the fuel reacted with air. In normal engine conditions, the minimum ignition delay occurs between 1.042 ms to 1.563 ms (10 to 15° CA TDC) at 1600 RPM engine speed [15]. A longer delay of combustion after the fuel injection can cause the longer combustion duration and leads to incomplete combustion of the fuel. In this simulation, the ignition delay of all blends was represented in Figure 3.

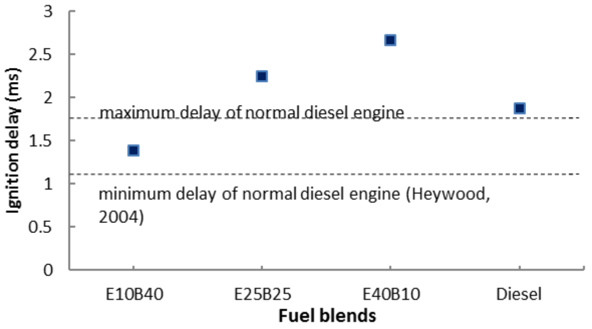
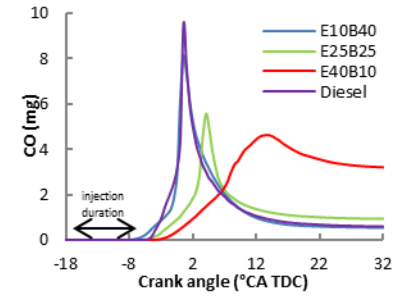


Fig. 3: Ignition delay of diesel-ethanol-PME blends at 1600 rpm engine speed

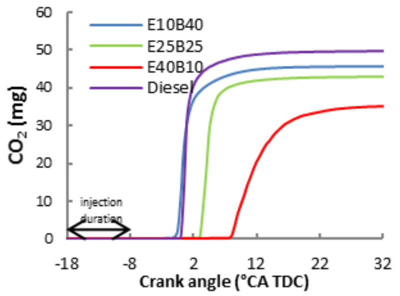
From the graph, E10B40 was identified to have a shorter ignition delay than other blends. Besides, the ignition of E10B40 also was in the range of normal ignition delay [15] and this concludes that E10B40 gives the best blends to avoid any longer delay of ignition. However, the ignition delay of diesel shows a bit longer than the maximum delay for a normal diesel engine. This is probably due to the injection duration was too short and reduce the air temperature and pressure.

3.2. Emission characteristics

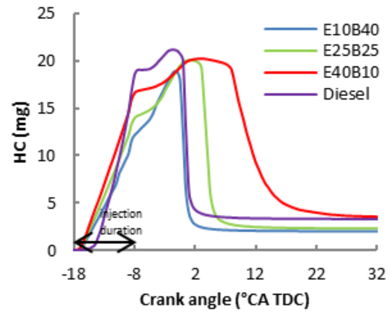
Shorter ignition delay and longer combustion duration will allow the fuel to completely burn in the engine and reduced the emission of carbon. Figure 4 shows the CO, CO2, HC and NOx emission of diesel-ethanol-PME blends from the start of injection (-18°CA BTDC) at 1600 RPM engine speed. The graph shows that the CO, CO2 and HC emission of diesel-ethanol-PME blends were lower than diesel fuel. Blending biofuels such as ethanol and biodiesel were able to reduce the carbon emission. During the combustion, the emission of CO and HC were rapidly increased and then slightly decreased before reached end of combustion (EOC) at -35 °CA BTDC. This is because biofuels contain higher oxygen contents and lower C/H ratio [3]. High oxygen contents help the fuel to combust easily and avoid the incomplete combustion.
The graph also shows the emission of NOx was completely different from CO, CO2 and HC emission. The graph shows that E10B40 emits slightly higher NOx emission than diesel, and a small percentage of PME reduced the emission of NOx. From this observation, a higher percentage of PME can lead to having higher NOx emission since the oxygen molecular contents in PME were very high. High oxygen contents of fuel increased the excessive oxygen contents during combustion and increased the in-cylinder temperature. At high temperature, oxygen can easily react with nitrogen and form NOx. In comparison with ethanol, PME contains lower oxygen contents than ethanol, but, the lower heating value of ethanol can reduce the temperature and result in lower NOx.



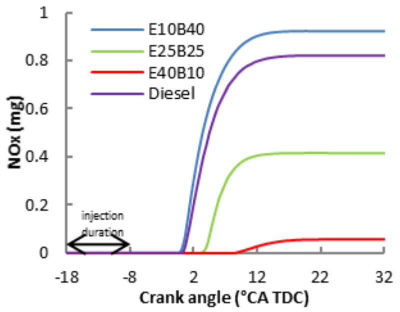
(a)



(b)



(c)



(d)

Fig. 4: CO (a), CO2 (b), HC (c) and NOx (d) emission of diesel-ethanol-PME blends at 1600 RPM engine speed

4. Conclusion

This paper aimed to study the combustion characteristics and emission of diesel-ethanol-PME blends in single cylinder diesel engine through a simulation works using CONVERGE CFD software based on a Yanmar TF90 direct injection single cylinder diesel engine parameter. 10-40% of PME was added to 10-40% of ethanol with a fixed percentage of 50% diesel fuel. The blends were mixed before entering the combustion chamber. This study can be concluded as below:

1. A high percentage of PME in diesel-ethanol-PME blends increases the in-cylinder pressure and HRR but slightly lower compared to diesel fuel due to its lower heating value.
2. The ignition delay of E10B40 is slightly shorter compared to diesel fuel. Shorter ignition delay results in longer combustion duration and incomplete combustion of fuel can be avoided for a better engine efficiency.
3. CO, CO2 and HC emission of diesel-ethanol-PME blends were decreased and lower than diesel fuel. However, NOx emission of E10B40 was slightly higher than diesel fuel. A higher percentage of PME increased the emission of NOx due to its higher oxygen contents. Meanwhile, the higher heating value of PME increased the pressure and temperature of a cylinder and increased the NOx emission.

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