Simulation of Injection Development of Diesel-Ethanol-Palm Oil Methyl Ester Blend in Direct Injection Diesel Engine

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ABSTRACT

Palm oil industry has become a major contributor to Malaysia's economic growth, and is included the National Key Economic Areas (NKEA) as part of an important thrust for the country to reach developed nation status by 2021. From an environmental and economic point of view, the use of palm oil methyl ester (PME) as fuel will also lead to a 'greener' future. This paper aims to study the effects of adding palm oil methyl ester (PME) in diesel-ethanol blended fuels for the development of fuel injection by using CONVERGE CFD software based on injection parameters of Yanmar TF90 diesel engine. Effects on the thermo-physical properties of the blended fuels were examined by blending 10% - 40% of ethanol with 10%-40% of PME in 50% diesel fuel. The injection development was analyzed with a focus on fuel penetration, droplets number, and droplet size. Every addition of 5% PME to the diesel-ethanol blends was found to increase fuel penetration by about 10% due to its high density and viscosity. A higher percentage of PME in the diesel-ethanol blends also generated smaller number of droplets, which were bigger in size. As for the distribution process, palm oil methyl ester (PME) led to slower combustion reaction. Mixing ethanol in these blends also slightly influenced the injection system where the penetration length of blends with high percentage of ethanol was higher and generated higher number of smaller-sized droplets due to the low viscosity, heating value and breaking energy to break the droplets. Both

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ethanol and PME were found to have an effect on the spray development in engine. The findings proved that high percentage of PME can lead to injection system failure and therefore, engine modification is required for it to work.

Keywords: *Palm Oil Methyl Ester (PME), Diesel-Ethanol Blends, Injection Development, Spray Penetration.*

Introduction

Announced in 2010, the 10th Malaysia Plan included an economic program with the target of transforming Malaysia into a developed nation by 2021; by focusing on the 12 National Key Economic Areas (NKEAs). The NKEAs among other things, acknowledge the palm oil industry to be a significant contributor to Malaysia's economic growth. To achieve productivity and sustainability targets, 8 Entry Point Projects (EEPs) have been identified, namely to accelerate replanting and new planting of oil palm, improve fresh fruit yields, improve worker productivity, increase oil extraction rate, develop biogas facilities, focus on high-value oleo derivatives, commercialise second-generation biofuels, and expand growth in food and health-based segments [1]. This has spurred many researchers to develop palm oil as biofuel to improve sustainable value-added activities in the automotive industry.

Diesel engine is known for its high potential in heavy duty industries [2]. Its ability to produce greater power output and efficiency helps the growth of various transportation industries. However, the problem of greenhouse gas emissions from the combustion of diesel fuel is detrimental to the environment, where diesel fuel is believed to emit higher levels of CO, CO_2 and hydrocarbons to the surroundings [3].

It is believed that biofuels such as alcohol and biodiesel can reduce greenhouse gas emissions, lessen dependence on petroleum, promote agricultural development in rural areas, and increase production of renewable energy [4, 5]. In addition, palm oil methyl ester (PME) is produced from edible bio-sources, which is a major feedstock alternative in Malaysia [6]. However, Malaysia seems to lack the production technology and investment. Therefore, ethanol is yet to be mass produced as biodiesel. Ethanol, with its lower viscosity, high oxygen content, low sulphur content and lower cetane number [7] may generate lower engine performance compared to other fuels.

Besides, PME is believed to have the potential to be used in diesel-ethanol blends to improve engine efficiency because PME has a very high cetane number, high energy and oxygen content, as well as heating value [8], [9]. In addition, PME is also known as the best stabilizing agent for diesel and ethanol blends that must be separated due to differences in their physical attributes [10].

However, PME has very high viscosity and density compared to diesel and ethanol, which can cause choking and fuel deposition on engine injection systems. When the tendency of the fluid to flow decreases, fuel will not disperse uniformly and larger droplets will form during injection, thereby leading to poor atomization [11].

Better atomization of fuel promises better combustion characteristics and engine performance. This is because better mixing of fuel with air in the combustion chamber can improve oxidation and fuel temperature [12]. Meanwhile, poor atomization leads to poorer combustion, and the fuel will not vaporize completely before it hits the piston wall of the cylinder [13]. If this happens, the cylinder wall may become wet and, in a low-temperature environment, piston to wall friction can occur, thereby reducing engine efficiency, causing engine wear and degrading the quality of the engine oil [14].

PME also has high boiling and evaporation points, which is also a major reason for the longer fuel penetration during injection. Different diesel-ethanol-PME compositions result in different injection qualities. The fuel penetration factor is affected by injection timing, nozzle position, injection pressure, discharge coefficient, and fuel properties [15]. Better fuel atomization can be brought about by having suitable injection parameters. In a simulation study, a normal diesel engine used the same injection system, and the fuel blend was directly injected into the cylinder through several hole-nozzles. A study by [16] showed that higher percentage of ethanol in biodiesel fuel can improve fuel atomization but reduce fuel penetration which is caused by lower density of ethanol, thereby resulting in a lower relative velocity of injection. This, in turn, slows the fuel penetration [17]. A high-density PME can contribute significantly to higher liquid penetration [18]. In addition, fuel blends with low boiling points tend to evaporate faster at low temperatures. Fuel blends with low boiling points can also easily disperse and evaporate, thus giving shorter penetration length [14].

Mixing PME with diesel or diesel-ethanol blends will slightly change the properties of the fuel because PME will increase density, viscosity and fuel power of the blend. In a fuel injection system, high-viscosity fuel can cause fuel deposition and injector choking, but biodiesel has very good lubrication that is able to control the corrosion of engine parts caused by ethanol [19]. Ethanol, with 5% water, can cause corrosion when it comes in contact with the engine wall or injector parts [20].

The objective of this paper is to study the injection development of different diesel-ethanol-PME blends. In this research, a simulation work was conducted using CONVERGE CFD software for the parameters of Yanmar TF90 single-cylinder diesel engine. Six compositions of diesel-ethanol-PME blends - consisting of 10% ethanol and 40% PME (E10B40), 15% ethanol and 35% PME (E15B35), 20% ethanol and 30% PME (E20B30), 25% ethanol and

25% PME (E25B25), 30% ethanol and 20% PME (E30B20) and 40% ethanol and 10% PME (E40B10) by volume - were used, and the properties were studied before the data were utilized in the simulation. The post-processing of the injection fuel penetration and injection droplet distribution was studied for all the blends at an engine speed of 1600 rpm. There was a small difference in the penetration lengths of the different fuel compositions, where each increment of 5% PME in blends shortened the penetration length around 5.79%. This indicates that the fuel compositions did have a significant influence on the fuel penetration when compared to the experiment conducted by [16].

Methodology

The methodology of this study comprises fuel properties test and simulation set-up.

Fuel Properties Test

In studying the fuel properties, each test on the fuel blend was carried out using diesel euro-2M, with hydrous 95% ethanol and PME. A density test was conducted, and the viscosity was obtained using a Kittiwake on-board viscometer test kit by immersing a stainless steel ball in the fuel. The travel time taken for the ball to reach the bottom of the test tube was recorded, and the kinematic viscosity, μ was calculated by using the formula expressed in Equation 1, where t is the travel time taken for the stainless steel ball to reach the bottom of the tube, k is the viscosity constant, ρ_f is the density of the stainless steel ball, and ρ is the density of the fuel.

$$\mu = t \text{ x } k \text{ x } (\rho_f - \rho) \tag{1}$$

In addition, a heating value test was conducted using a bomb calorimeter. 50 ml of diesel was mixed in advance with PME, followed by ethanol [10]. This method was used to keep the blends stable for a longer period since diesel and ethanol blends are immiscible. All the properties of the fuel blends are summarized in Table 1.

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

Fuel composition (vol%)	**Density (kg/m3)**	**Viscosity (cSt)**	**Heating value (kJ/kg)**
D100	825.0	3.13	44.783
B100	857.478	4.55	37.270
E100	793.063	2.44	26.960
E40B10	809.123	2.685	38.609
E30B20	819.513	3.005	39.371
E25B25	827.770	3.111	39.878
E20B30	836.213	3.381	40.346
E10B40	848.763	4.209	41.274

Simulation setup

From the study of the properties, an estimate of the thermo-physical properties was made to obtain all the required data for the simulation. Table 2 shows the thermo-physical properties of diesel (nC_7H_{16}), ethanol (C_2H_5OH) and PME ($C_{16}H_{34}O_2$). The properties of diesel and ethanol were set as the default properties, while the properties of PME were set as the constant for all conditions and temperatures. This study used CONVERGE CFD software based on the parameters of a Yanmar TF90 single-cylinder diesel engine to analyse the combustion of multi-fuel components involving diesel, ethanol and PME. 10%, 15%, 20%, 25%, 30% and 40% of ethanol are blended together with 40%, 35%, 30%, 25%, 20% and 10% ethanol in 50% diesel by volume. All the case studies were operated using a 3D engine model using CONVERGE CFD software.

Data on the reaction mechanism was important in the simulation work as it comprised information on the elements and species of the fuel used in the simulation. However, the reaction mechanism of palm oil methyl ester was very large, and it was necessary to conduct a mechanism reduction process in order to have a better fuel reaction mechanism that would be compatible with the software. With a pressure range of 20-40 bars, temperature of 800-1200 K and an equivalence ratio of 0.5-2.0, a Zdcase and a new mechanism were generated. In injection modelling, the injection shape rate and fuel composition ratio were set up in spray modelling. The injection shape rate is a simulation of the fuel control system to provide effective fuel controls to be injected into the engine cylinder. The injection shape rate is influenced by the injection pressure, discharge coefficient, nozzle diameter and engine speed. All these parameters affect the fuel injection rate and also improve engine combustion as well as emission reduction.

Table 2: Thermo-physical properties of diesel, ethanol and PME in simulation setup

Properties	**Diesel**	**Ethanol**	**B100**
Critical temperature (K)	540.3	513.9	780
Density (kg/m^3)	683.75	789.37	888
Viscosity (N.s/m^2)	1.22x10^{-6} - 3.77x10^{-3}	4.04x10^{-5} - 6.0x10^{-3}	7.75x10^{-3}
Liquid surface tension (N/m)	1.0x10^{-5} - 2.54x10^{-2}	4.1x10^{-4} - 2.44x10^{-2}	3.7x10^{-2}
Heat of vaporization (kJ/kg)	106 - 486	369 - 1300	459
Vapor pressure (MPa)	0 - 3.03	0 - 6.55	0
Specific heat capacity (kJ/kg.K)	2.020 – 3.845	2.230 – 6.812	2.020
Thermal conductivity (W/m.K)	0.06379 - 0.156	0.11179 - 0.1865	0.0661

In this simulation study, the engine was set up to run at a speed of 1600 rpm. The injection shape rate was generated using a virtual injection rate generator created by Universitat Politecnica de Valencia [21], where a maximum injection pressure of 19.613 MPa was obtained from an engine with a nozzle diameter of 0.22 mm and a discharge coefficient of 0.6088. The engine specifications and the simulation setup are explained in Table 3.

Table 3: Engine specifications and simulation setup

	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 TDC
Injection pressure	200 bar
Injection duration	10 ˚CA TDC
Engine speed	1600 rpm
Number of injection nozzle	4
Nozzle diameter	0.22 mm
Bowl depth	16 mm
Bowl diameter	46.3 mm

Result and Discussion

The results and discussion of the study shall focus on fuel penetration and spray distribution.

Fuel penetration

Figure 1 shows the in-cylinder pressure and fuel penetration length of different fuel blends during injection from -18°CA BTDC to 20°CA ATDC. Upon injection, the fuel travelled rapidly through the chamber until reaching the piston bowl wall at -12.87°CA BTDC and slightly decreased as the piston approached TDC. As indicated by the in-cylinder pressure, the liquid penetration length was shorter when the in-cylinder pressure increased. This was due to atomization of fuel in the air that reduced penetration and finally increased while occupying the space in the cylinder. From the results, the penetration length of diesel-ethanol-PME blends did not register major change to the penetration before TDC. As explained from Yinjie Ma *et al*. research, penetration of different fuel blends during this time has no significant change because there is no obvious change to the fuel physical properties [22].

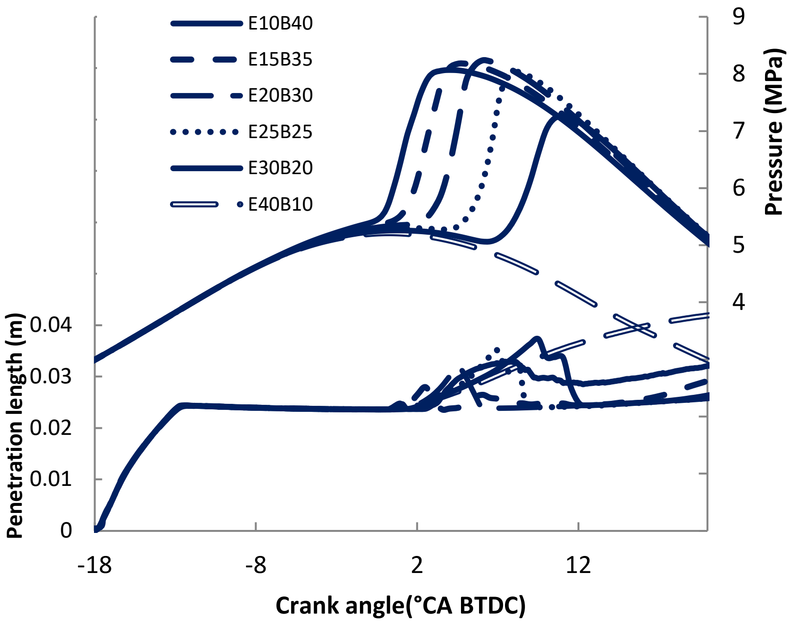

Figure 1: In-cylinder pressure and penetration length of different fuel compositions

However, when the piston reached TDC, fuels started to react with the air and penetration started to increase depending on the fuel physical properties such as viscosity and surface tension. The graph also shows that increment of PME percentage in the blends shows shorter penetration due to weak atomization upon reaching TDC. This is because injection pressure of the engine used in this research was very low compared to the other engines. Therefore, diesel-ethanol-PME blends operation may require higher injection pressure.

A shorter penetration can cause slower combustion and evaporation. PME has slightly higher heating value compared to ethanol but lower than diesel. The differences meant that the blends with a high percentage of ethanol and PME needed a longer time to combust when compared with diesel. However, different percentage of ethanol and biodiesel in diesel has a very small effect on the spray penetration due to the slight difference in density and viscosity of the blends [16].

Spray distribution

Figure 2 shows the number of fuel droplets profile where the number of droplets rapidly increased at the start of injection at -18°CA BTDC until it reached -3°CA BTDC. This is due to the high pressure from the injection that enabled it to penetrate the fuel further. The number of droplets then decreased after the piston reached -3°CA BTDC. This was because the pressure rise in the cylinder exceeded the pressure from injection since the cylinder volume decreased as piston reached TDC. High penetration of fuels can lead to a better atomization. As proved by Yinjie Ma *et al*, high ethanol contents have higher spray volume that indicates ethanol has bigger number of droplets [22].

However, having high number of droplets for high percentage of ethanol in blends leads to faster evaporation due to ethanol properties that are easy to evaporate and disperse in the air. Therefore, high PME contents are helpful to overcome the problem posed by ethanol but high PME contents will lead to smaller amount of droplets since droplets of fuel becomes bigger due to high viscosity and high surface tension of the fuel blends. This is clearly shown in the graph, where at -3°CA the number of droplets for all blends is obviously different with around 4.1% difference for each addition of 5% PME.

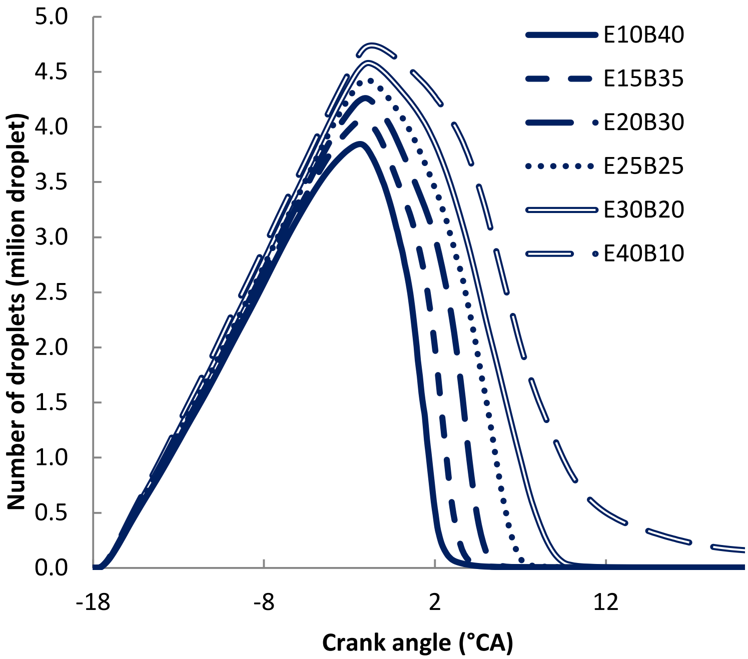

Figure 2: Number of droplets profile of different diesel-ethanol-PME blended fuel.

Figure 3 shows the spray droplet distribution of different fuel compositions during injection as expressed in Sauter mean diameter (SMD). The SMD is the average droplet size with the same surface/volume ratio as the total spray [23]. As the percentage of ethanol in the blends was higher than that of PME, SMD was smaller than other blends but became higher after the piston left TDC since the penetration of fuels was drastically longer and with smaller spray cone angle, the intensity of air was reduced and led to bigger droplet size. This was also due to the density and viscosity of ethanol, being lower than of PME, leading to a lower droplet size for better evaporation. A lower fuel density resulted in a lower relative velocity between the injected spray and the ambient gas [15, 16]. However, after the piston reached 85°CA ATDC, SMD value for high ethanol blends increased and was higher than the other blends. Hence, the lower relative velocity resulted in a lower fuel penetration and smaller droplet distribution. Although there was only a small difference in the fuel penetration and fuel droplet diameter for all the fuel blends, the differences in the thermo-physical properties did have any effect on the liquid dispersion.

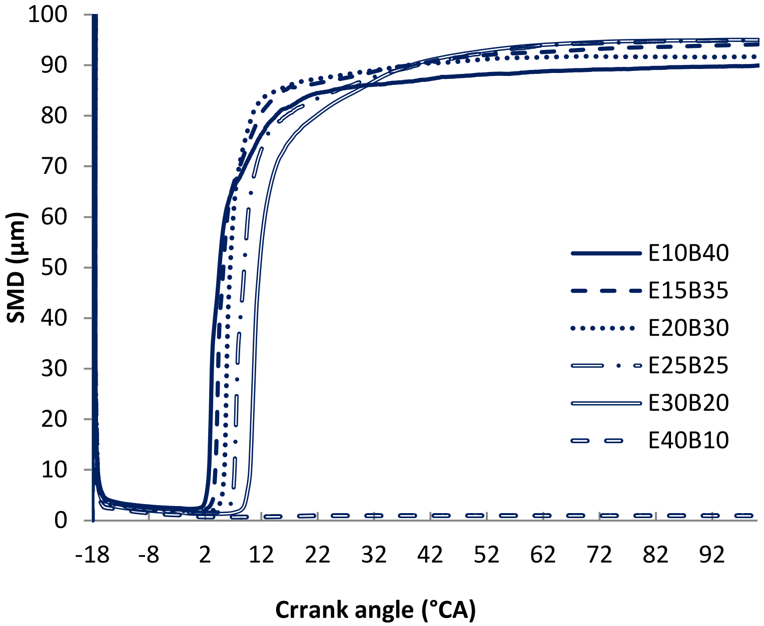

Figure 3: Spray droplet size distribution of various fuel compositions

Conclusions

A simulation study was conducted using CONVERGE CFD software based on the parameters of a Yanmar TF90 single-cylinder diesel engine to investigate the effects of various PME-diesel-ethanol blends on the injection system. The focus of this work was to study the injection development of diesel-ethanol-PME blends in terms of fuel penetration and droplet distribution. PME is known as a fuel with a high viscosity, high density and low heating value compared to diesel, and the following conclusions were reached.

Blending higher PME contents in diesel-ethanol blends resulted a shorter fuel penetration after the piston reached TDC due to high viscosity of blends with the average difference around 5.75% when PME were added with 5% increment and smaller SMD distribution in low injection pressure engines compared to higher injection pressure engines from the previous study. In addition, adding high percentage of PME to diesel-ethanol blends also slightly reduced the droplets number since the droplets average size was bigger than the blends with high ethanol percentage measured as SMD. The droplets number was lower due to the high density, viscosity and surface tension of PME with the percentage different around 4.1% for each 5% PME addition. Finally, the addition of PME to diesel-ethanol blends was found to increase droplet distribution and the Sauter mean diameter (SMD) of the droplets due to the high viscosity and surface tension of the droplets.

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