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Investigation of diesel-ethanol blended fuel properties with palm methyl ester as co-solvent and blends enhancer

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Abstract. Diesel engine is known as the most efficient engine with high efficiency and power but always reported as high fuel emission. Malaysia National Automotive Policy (NAP) was targeting to improve competitive regional focusing on green technology development in reducing the emission of the engine. Therefore, ethanol was introduced to reduce the emission of the engine and while increasing its performance, Palm methyl ester was introduced as blend enhancer to improve engine performance and improve diesel-ethanol blends stability. This paper aimed to study the characteristics of the blends and to prove the ability of palm-methyl-ester as co-solvent in ethanol-diesel blends. Stability and thermophysical test were carried out for different fuel compositions. The stability of diesel-ethanol blended was proved to be improved with the addition of PME at the longer period and the stability of the blends changed depending on temperature and ethanol content. Density and viscosity of diesel-ethanol-PME blends also give higher result than diesel-ethanol blends and it's proved that PME is able to increase density and viscosity of blends. Besides, heating value of the blends also increases with the increasing PME in diesel-ethanol blends.

1 Introduction

The power of diesel engine in producing a better power output and efficiency especially to the heavy load transportation makes the diesel engine as one of the main focus of the researchers to innovate and develop the engine potential to a better performance and better emission. Diesel engine is a compression ignition engine that the power and efficiency of the engine are strongly depending on the compression ratio of the engine. However, diesel engine gives high carbon emission since diesel fuel was made up from crude oil that leads to high carbon emission and pollution if the incomplete combustion occurs during the

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combustion process. Along with the NAP (National Automotive policy) review in 2014, biofuels was selected as the main focus as new green technology initiative for the development of technology and human capital where the new goals of NAP 2014 are to develop a competitive and capable domestic automotive industry by pointed Malaysia as the regional automotive hub in Energy Efficient Vehicle (EEV) and to increase value-added activities in a sustainable way while continuously developing domestic capabilities [1].

Therefore, ethanol was chosen as effective biofuels to reduce the emission concentration from diesel combustion by contributing its potential due to its availability in large volume and second generation process in future [2]. Ethanol can be blended with diesel in the tank or injected into the cylinder to reduce the exhausted pollution [3]. Ethanol is easy to produce because it is produced from the fermentation of sugar such as sugar cane, grass, corn, barley sugar, etc [4]. Besides, it is capable of reducing the harmful exhaust emission such as CO, CO2, SOx, smoke opacity and particulate matter [5]. However, ethanol is not miscible in diesel fuel due to their physical properties difference and ethanol contains high oxygen content that leads to high NOx emission [6][7] and knocks problem. Besides, ethanol has extremely low cetane number [8] that increase the ignition time delay which leads to knock problem. All ethanol thermo-physical properties are explained in Table 1. Therefore, an emulsifier or co-solvent are needed to maintain the stability of diesel ethanol blend [2] and to act as fuel enhancer to improve engine performance and reducing NO emission. Many researchers have studied about the performance and emission of the diesel ethanol blend. They found out that the brake thermal efficiency and fuel consumption of blends may increase [5] and engine power will slightly reduce as well as the emission. Brake thermal efficiency are technically related to the heating value of the blends. Although the heating value of ethanol blends usually very low, the BTE of the engine may not always be increased depending on the brake power of the engine. Therefore, as the percentage of ethanol in diesel increase, thermal efficiency also may decrease [9].

Stability of diesel ethanol blends is strongly dependent on a few factors such as temperature [10], water content of ethanol, aromatic hydrocarbon, paraffin contents in diesel [3]. Stability problem of diesel ethanol blend may lead to the very dangerous situation to engine event to the most catastrophic consequences [11]. This is because ethanol is known as good water absorber and even a small amount of ethanol was added to diesel, the ethanol will pick up and absorb the water and when the saturation point of the blends are reached, two or three distinct layers are formed. If the pickup tube draws the fuel at water layer, the engine will experience thermal shock or hydro lock problem [10].

Palm Methyl Ester (PME) is an example of fatty acid methyl ester where the physical properties of fatty acid are closer to diesel fuel. PME are made of palm oil by esterification process. In esterification process, a glyceride reacts with an alcohol with the presence of a catalyst to form a fatty acid ester with alcohol. Malaysia was known as the world largest palm oil manufacturer and largest exporter which producing almost 15.8 million tons per year[12] and palm oil production process was the cheapest process among another biodiesel source. PME has the ability as fuel enhancer especially for diesel ethanol blends since it has very good properties as shown in table 1 with high cetane number that balancing the cetane number reduction when ethanol was added to diesel fuel. Cetane number is a very important parameter in the engine where the higher cetane number gives better engine efficiency with lower ignition delay in the engine. Besides, PME has low sulphur content that able to reduce Sox that lead to the poisonous environment. From the emission view, all biofuels such as PME and ethanol produces lower emission of CO, CO2, SOx, PM and HC compared to diesel. However, the oxygen content in biofuels gives some effect on NOx emission because oxygen contents in biofuels lead the combustion into lean combustion and at a very high-temperature, nitrogen gas may split to produce NOx. When discussing the diesel ethanol stability, PME has the special ability as co-solvent or amphiphile (surface reactant agent) [2] where PME has the most stable HLB (Hydrophile-Lipophile Balance) value for w/o emulsions. PME was used as co-solvent to stabilize the blends at a different temperature.

Table 1. Properties of diesel, ethanol and PME [13].

	Diesel euro 2M	**Ethanol**	**PME**
Chemical formula	C_3-C_{25}	C_2H_5OH	C19H35O2
Density (kg/L) at 15˚C	0.81-0.87	0.796	0.8754
Kinematic viscosity, (mm^2/s)	1.9-4.1	1.4	4.55
Cetane number	49	8	70
Cloud point, ˚C	19		15
Flashpoint, ˚C	60	55	170
Sulphur contents, (mg/kg)	500		2
Heating value, (MJ/kg)	43.4	28.8	36.76
Autoignition temperature (˚C)	315	422.8	342

The blend stability test is a method to determine the most stable blend for a further method for fuel properties. The stability of the blend is an important parameter to predict the highest ethanol percentage in avoiding the separation process of the fuel. If the separation of fuel happened after the addition of PME, the blend was categorized as a non-stable blend. The properties of the blends such as viscosity and heating value always related to engine efficiency. This fuel properties research was conducted to find the best blend by using the relation of viscosity, density, and heating value to the fuel consumption and engine performance. Viscosity played a very important role in combustion quality where it is strongly related to the injector in the engine. The viscosity of the fuel in the regular diesel engine must obey the injector regulation for a diesel engine with a standard viscosity of diesel fuel. The viscosity of fuel must be checked and have to maintain to the closest limit of diesel fuel viscosity which is around 1.7-4.1 cSt at 40˚C [14]. Controlling the viscosity of fuel helps to provide a proper atomization of fuel during combustion [15] which leads to complete combustion and help the emission control due to incomplete combustion[16]. The density and viscosity of diesel-ethanol blends were said to decrease as the ethanol contents increase which proved by De Gang Li [17]as shown in Figure 1.

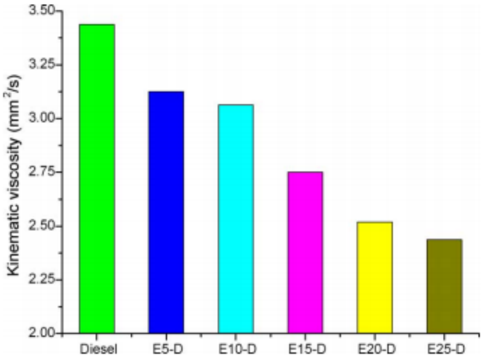

Fig. 1. Kinematic viscosity of blend fuels and diesel fuel [17].

Lower heating value is an another important properties in fuel to produce a better engine performance and engine emission. Fuel conversion efficiency or brake thermal efficiency of the engine is the ratio of brake power to the fuel power where the fuel power are related to the lower heating value [18]. The relation was explained in eq. (1) below where fuel power is inversely proportional to BTE.

$$\text{Brake thermal efficiency (BTE)} = \frac{\text{Brake power}}{\text{fuel power}} \qquad (1)$$

Fuel power is related to the lower heating value which shown in eq. (2) where the product of mass flow rate of fuel, m_f and low heating value, LHV are indicated the fuel power and it is shown that the heating value of fuel is directly proportional to fuel power.

$$Fuel\,power = m_f * LHV \qquad (2)$$

Ethanol and biodiesel release very low heating in combustion due to its high oxygen content [13]. From the relation shown in eq. 2, the lower heating value of the diesel ethanol blends may reduce the fuel power and increase the brake thermal efficiency. Fuel power is the power returned if the energy released from burning fuel in the engine that converted into mechanical power that produces through the shaft rotation. Thermal efficiency of the engine usually was increased when the engine speed increase up to the maximum value and decreased at some points due to momentum loss of the engine motion when the piston moves too fast [19]. Therefore, all the properties studies are very important in combustion engine for better emission and performance. In accordance with this importance, this research was focused on studying the properties of the diesel-ethanol-PME blends which including stability, density, viscosity and heating value. This research also aimed to proved that the stability of diesel-ethanol blends can be improved by using PME as co-solvent and blends enhancer.

2 Experimental setup

2.1 Materials

Diesel euro 2M was used to study the blend properties with hydrous alcohol (Ethanol 95 %) with a different percentage. The fuel percentage of diesel ethanol blends are shown in table 2. The blends were placed in the flasks with a maximum volume of 100 ml for each blend. 10 ml of PME was added into each diesel ethanol blend to study the stability of diesel ethanol PME blends

Table 2. Diesel-ethanol blends percentage for blend stability.

Composition	**Diesel (%)**	**Ethanol (%)**
D100	100	0
E10	90	10
E20	80	20
E30	70	30
E40	60	40
E50	50	50
E60	40	60
E70	30	70
E80	20	80
E90	10	90

Besides the blend stability test, a few blend properties were handled to obtain the thermal physical properties such as density, viscosity, and lower heating value. All these parameters are the requirement for the simulation analysis. The fuel percentage of the blends was explained in table 3.

Table 3. Diesel-ethanol blends percentage for density, viscosity and heating value test.

Composition	Diesel (%)	Ethanol (%)	PME (%)
E40B10	50	40	10
E35B15	50	35	15
E30B20	50	30	20
E25B25	50	25	25
E20B30	50	20	30
E15B35	50	15	35
E10B40	50	10	40
E5B45	50	5	45

2.2 Fuel properties test

2.2.1 Blend stability

Diesel-ethanol blend is well known as immiscible blends that may affect the engine condition. Diesel ethanol blend was mixed with different percentages to study the separation effects and time of separation of the blends. Besides, the stability of the blends was studied at a different temperature which is at 27˚C and 16˚C. Based on the theory, stability of the diesel ethanol blends is strongly dependent on temperature. The stability of blends was observed during the day up to 3 times and the time separation was recorded.

2.2.2 Density

The density of the blends was measured by using a hydrometer Kittiwake onboard test kit. The density was measured at two different temperature of 16˚C and 27˚C with the relation of density as explained in eq. (3). Density is the ratio of the mass to the volume of the fuel determined in ASTM D4052. After the fuel was mixed, the fuel was filled in a 100ml beaker and the mass of fuel was measured. The mass of a 100ml glass beaker was 19.8737g. The average of mass and volume were obtained after repeating the measurement for three times.

$$\rho = \frac{m}{V} \tag{3}$$

2.2.3 Viscosity

The viscosity is a measure of the resistance of the fuel to the gradual deformation by shear stress or tensile stress or uses the concept of the thickness of fuel. Viscosity also is strongly related to fuel consumption in the combustion process. The viscosity of fuel is measured by immersing a stainless steel ball into an onboard viscometer where the gravitational principle was applied. The ball will travel from top to bottom of glass under gravity influence. The specification of viscometer used in this experiment was described in table 4.

Table 4. Specification of the onboard viscometer.

Specification	Diesel (%)
Brand	Kittiwake
Density of stainless steel,ρ (g/ml)	8.02
Viscosity constant, k	≈0.34

All this specification are used in finding the kinematic viscosity based on the traveling time of stainless steel ball by using the equation (4). Travelling time of the steel ball was recorded from the top to the bottom of the glass which marked with a red line and was repeated for 3 times for better accuracy.

$$\mu = t \text{ x } k \text{ x } (\rho - \rho_f) \tag{4}$$

2.2.4 Heating value

Lower heating value (LHV) is an important consideration when selecting a fuel because engine efficiency usually quoted based on lower heating value. Heating value is an important parameter in determining the fuel power in combustion process within fuel and air in the combustion chamber. Heating value is determined by using IKA C 200 Oxygen bomb calorimeter based on the standard test method ASTM D240. A small amount of fuel sample placed in sample cup was weighed and placed in sealed bomb. A sufficient amount of oxygen supplied to the sealed bomb at 30 bar. Then, the sealed bomb was placed in the container filled with bath water at 15 ℃. The temperature rise measured in the bomb chamber resulting the lower heating value or calorific value at the specific mass of fuel. Calorific value is defined as the energy released when a unit mass of fuel are completely burned in the air. Therefore, to achieve a certain amount of fuel power, a sufficient amount of fuel needed to provide maximum engine power.

3 Results and discussion

Diesel-ethanol PME blends have very special properties which change the behavior of the diesel fuel in diesel engine. Ethanol gives a very big impact on the diesel fuel because it has very low density, low viscosity, low heating value and high water content. Due to the high water and oxygen content in ethanol, the blend of diesel and ethanol at normal condition resulting in a poor combination. This is observed when the separation layer or known as lipid bilayer is formed in between the solution of diesel and ethanol after some period. When ethanol was added into diesel fuel from 10% up to 90%, the formation of lipid bilayer were formed only for E40 (40%), E50 (50%), E60 (60%) and E70 (70%). Before the separation layer was formed, the blend was in crystalline single phase condition. While E90, E80, E10, E20 and E30 formed in single clear phase from the beginning. This is because the diesel contents in E90 and E80 were too small to see the formation of the layer formed as well as ethanol contents in E10, E20, and E30. However, the separation layer for E30 was formed at a lower temperature. This proves that the blending stability is change depending on the temperature and ethanol content in diesel fuel. The separation result at different temperature was explained in triangle phase diagram as shown in figure 2 (a) and

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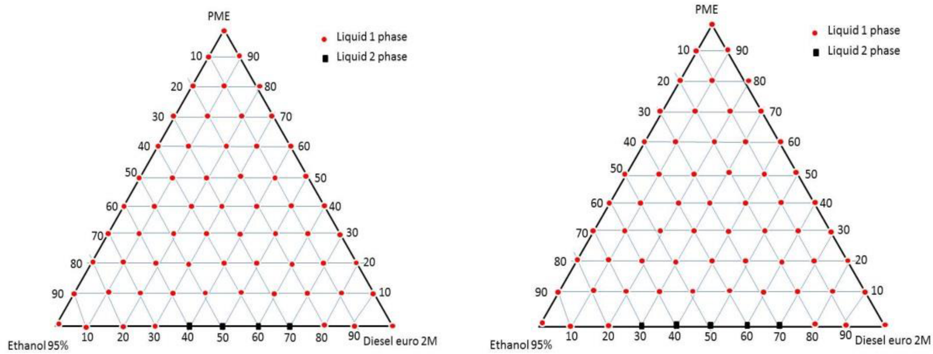
(b). After the addition of 10% of biodiesel, the blends were stable up to more than diesel ethanol blends.



(a) (b)

Fig. 2. Triangle phase diesel-ethanol PME blends at 27℃ (a) and 16℃ (b).

Since the density of ethanol is much lower than diesel fuel, the separation layer formed placed ethanol as an upper layer and diesel as a lower layer and separated by a lipid bilayer. The height of the lipid bilayer was measured and analyzed as in figure 3.

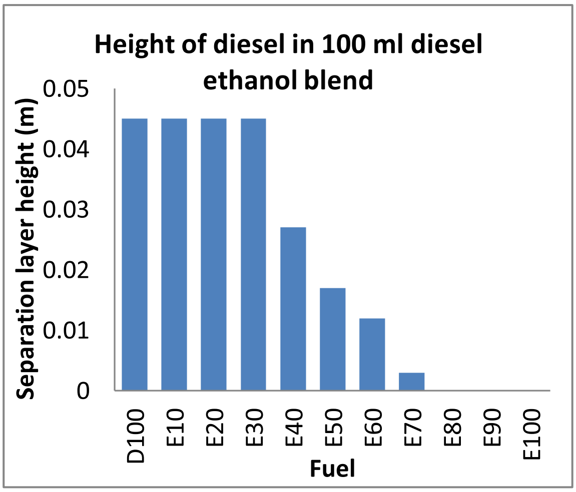


Fig. 3. Height of separation layer formed at 27℃.

The separation behavior is then explained with the separation time differences for the blends where the behavior of lipid bilayer may become the main reason of the change. Lipid bilayer is membrane layer that formed from two solution layer that contains hydrophobic head and hydrophilic tail and allows the molecule to pass through it and separate the fuel in meantime. From the graph shown in figure 4, the separation time of the blends are not uniform and always changed after a few experiments for separation were made. From the observation, E60 and E70 give a very unstable result where time separation of E60 and E70 are referred to the right axis and E340 and E50 are refer to left axis.The separation time behavior was observed for E30, E40, E50, E60 and E70 to study the

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separation layer behavior. This change happened due to the mechanical change applied to the blends. When a small force applied to the blends, the compact membrane layer molecule changes its structure and allow more diesel molecule to pass through the membrane caused the complete separation to occur. From this observation, the determination of separation time for optimization is not valid. Adding a co-solvent like PME gives the advantage for the blend to keep stable for a longer period where there is no separation occur after a longer period.

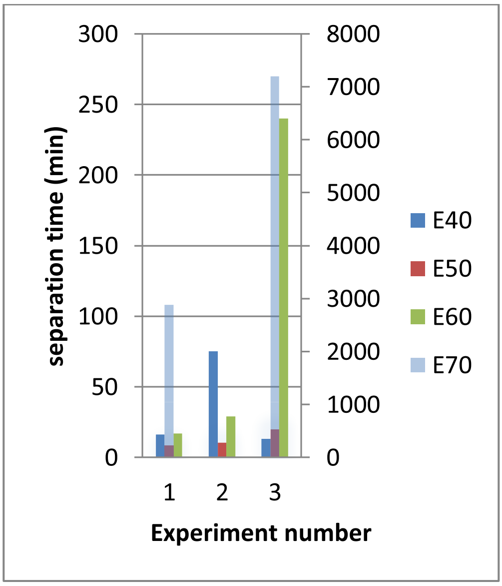

Fig. 4. Separation time of diesel-ethanol blends at 16℃.

Ethanol is a fuel that has a very low density and viscosity compare to diesel and biodiesel. From the graph shown in figure 6, the density of the blend decrease as the increasing of ethanol percentage and higher density will lead to higher viscosity as well [20]. This density of the blends are related to the viscosity which shown in figure 5 and from the equation of kinematic viscosity, the viscosity is strongly dependent on the density of the fuel where the density also decrease as the increasing of ethanol in blends. This proved that ethanol has lower density and viscosity. As the addition of PME in diesel ethanol blends, the density and the viscosity of the blends increased since the viscosity of PME is naturally higher than diesel and ethanol. In this blends, ethanol has the lowest density and viscosity. Therefore, the addition of PME in diesel was able to stabilize the density and viscosity of the blends to meet the standard regulation of blends' viscosity in a regular engine.

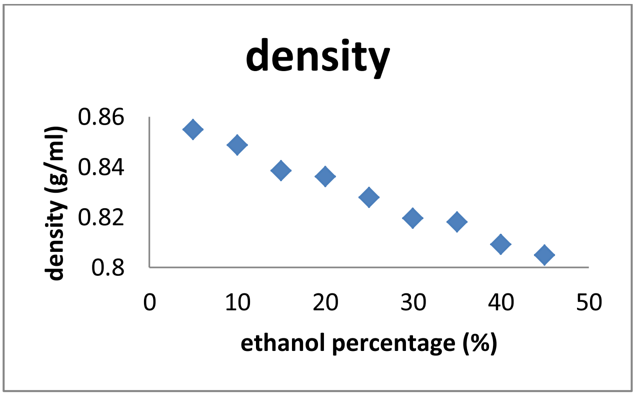

Fig. 5. Density of diesel-ethanol-PME blends at 27℃.

Viscosity plays an important role for engine performance and fuel consumption. In order to maintain the engine without any modification on engine cylinder and injector, the viscosity of the blends has to meet the diesel viscosity regulation which is around 1.7-4.1 cSt (1.7E-06 – 4.1E-06 m^2/s). From the graph in figure 6, the viscosity of the blends measured obeyed the viscosity regulation of diesel engine injector except for the blend with5%, 10% ethanol. This is because PME content in these blends is very high up to 40 and 45%. PME has a very high viscosity that affects the blends viscosity. The viscosity of diesel-ethanol-PME blends is increased around 10% when compared to the viscosity of diesel ethanol from [17] in figure1. The higher viscosity of fuel will increase the amount of fuel injected due to the delay of nozzle needle valve opening cause the reduction of energy conversion effectiveness. This is because the injector valve will need more fuel to be injected to meet the required heating value for the perfect piston motion.

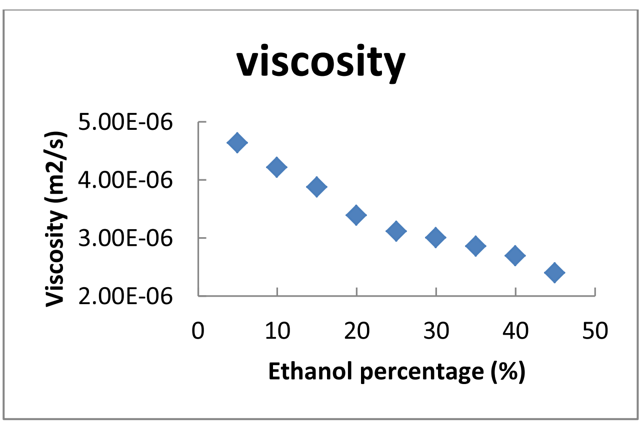

Fig. 6. Viscosity of diesel-ethanol-PME blends at 27℃.

Since biodiesel has a very low heating value, the heating value or calorific value of blends also decreased. Heating value is always related to engine performance and emission. From the graph shown in figure 7, the heating value of blends is decreased as the percentage of ethanol decrease and PME increase. This is because the water contents in biofuels are very high. The water content is vaporized during the combustion, taking up the heat produced from the combustion and lowering the heating value of fuel[6]. Since the heating values of the blends are decreased as the biofuels increased in blends, the brake thermal efficiency of the engine can be predicted to increase

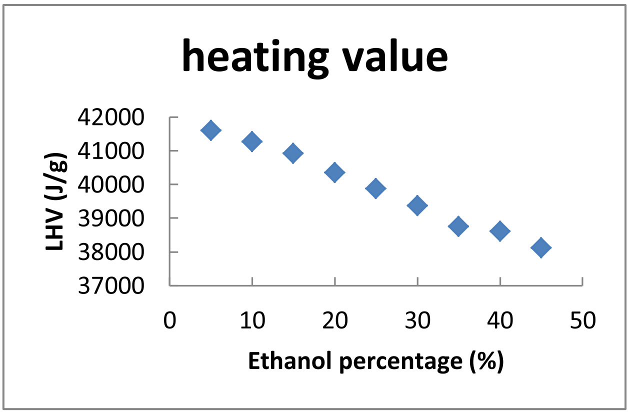

Fig. 7. Low heating value of diesel-ethanol-PME blends.

4 Conclusions

In this paper, the blends properties were observed and studied to find the best blends that regulate the standard engine requirement such as density, viscosity and low heating value of the blends. As the biofuels were used in diesel blends, the behaviors of the fuels are changed due to the biofuels properties. Diesel-ethanol blends are very unstable and formed a separation layer at some period and when PME was added into the blends, the stability of the blends are more stable up to more than two weeks. Based on the density and viscosity test, ethanol affects the density and viscosity of the blends since ethanol has lower density and viscosity. When more than 40% of PME added to diesel, the viscosity value was too high and beyond the standard viscosity regulation for standard engine injection. Therefore, the fuel blends with higher than 40% PME was not suitable to be used in the normal engine without any modification.

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