

# An Experimental Study on the Solubility of a Diesel-Ethanol Blend and on the Performance of a Diesel Engine Fueled with Diesel-Biodiesel - Ethanol Blends

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## Abstract

The phase stability of DE and DBE blends at different component concentrations, as well as the effects of using DBE blends including ethanol of various proportions on a CI engine performance are experimentally investigated. The engine was operated with DBE blends having 5, 10, 15 and 20% ethanol with fixed 10% biodiesel on a volume basis, to solve the phase separation problem, as well as on diesel fuel alone at constant load and at engine speed ranges from 800 to 1600 rpm for each run. The experimental results of the phase stability revealed that the DE blends is not stable and separated after 2, 5, 24 and 80 hours, for 20%, 15%, 10% and 5% ethanol concentration, respectively. Whereas for DBE blends the separation time is longer than of the first system and reached 1, 3 and 9 days for 20%, 15%, 10% ethanol concentration, respectively. The blend of DBE5 was of the best stability with very little separation. The experimental results of the engine performance indicated that the equivalence air-fuel ratio and the brake specific fuel consumption for the fuel blends are higher than that of diesel fuel and increases with the increase of the ethanol concentration in the blends. The brake power for the fuel blend of 5% ethanol concentration is close to that of diesel fuel and decreases with higher concentrations. The brake thermal efficiency was increased with fuel blends of 5 and 10% ethanol concentration and decreases with a higher ethanol proportion in the blends. In conclusion, among the different fuel blends, the blends containing 5 and 10% ethanol concentration are the most suited for CI engines due to its acceptable engine performance and to the fuels solubility.

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Keywords: Ethanol; Biodiesel; Fuel Blends; Solubility; Engine Performance

## 1. Introduction

The increase on energy demand, environmental concern of the global warming and climate change and increasing petroleum price in the worldwide has greatly increased the interests of the application study of alternative fuels to internal combustion engines. Among these alternative fuels, biodiesel and diesohol (diesel – ethanol blends) have received much attention in recent years for Compression Ignition (CI) diesel engines. Ethanol is regards as a renewable fuel because it can be made from many types of raw materials such as corn, sugar cane, sugar beets, molasses, cassava, waste biomass materials, sorghum, barley, maize, etc. [1, 2]. Ethanol has been successfully used to blend with gasoline fuel as part of the alternative to reduce the consumption of conventional gasoline [3, 4]. However, it has not been commercially used to replace part of diesel fuel to diesel engines, because the barriers for application have not been overcome yet, due to the difference in chemical and physical properties between ethanol and diesel fuel. At present, significant investigations of the potential application of ethanol - diesel (ED) fuel blends on diesel

engine have been carried out. Hansen et al. [5] investigated the Cummins engine performance with 15 % ED fuel blends and found that the engine power decreases by about of 7 to 10 % and the brake thermal efficiency increases by about of 2 – 3 % at rated speed. Kass et al. [6] tested the torque output from the same model engine with two blends containing 10 % and 15 % ethanol and reported an approximate 8 % engine power reduction for both fuel blends. Huang et al. [7] investigated the engine performance and exhaust emissions of diesel engine when using 10%, 20%, 25% and 30% ethanol-blended diesel fuels. In that study, the results showed that the brake thermal efficiencies decreased with increasing amount of ethanol in the blended fuels. Rakopoulos et al. [8] studied the effects of ethanol blends with diesel fuel, with 5% and 10% (v/v) on the performance and emissions of a turbocharged direct injection diesel engine. The results showed that increasing the ethanol amount in the fuel blend increased the brake specific fuel consumption and decreased the brake thermal efficiency. Results of [9–11] shows that diesel fuel blended with ethanol up to 10 vol. % can be used to solve the fuel shortage problems, increase the energy conversion efficiency, improve fuel economy and reduce its harmful emissions. Also using ED fuel blends on diesel engine can yield a significant reduction of

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carbon monoxide and nitrogen oxide [12] and particulate matter emissions [13, 14]. Nevertheless, a major drawback with using ethanol in diesel engines is the limited solubility of ethanol in diesel fuel; therefore, phase separation and water tolerance in ethanol–diesel blend fuel are vital problems.

The phase separation can be prevented in two ways: by adding an emulsifier that acts to suspend small droplets of ethanol within the diesel fuel, or by adding a co-solvent that acts as a bridging agent through molecular compatibility and bonding to produce a homogeneous blend [15-18]. Emulsification usually requires heating and blending steps to generate the final blend, whereas co-solvents allow fuels to be “splash-blended”, thus simplifying the blending process.

Currently, biodiesel is known to act as an additive or emulsifier due to its potential to improve the solubility of ethanol in diesel fuel and could improve lubricity of ethanol over a wide range of temperatures and blend properties [19–22]. Fernando and Hanna [23] determined the relative compatibilities of ethanol, biodiesel, and diesel fuel. They concluded that ethanol–biodiesel–diesel (EB-diesel) fuel blend, micro emulsions, are stable well below sub-zero temperatures and have shown equal or superior fuel properties to regular diesel fuel. Barabas and Todorut [24] studied the key fuel properties of the EB-diesel blends and investigated that blends have the same or very close density and viscosity to standardized diesel fuel. The surface tensions of the blends are only 20% higher than that of diesel fuels. In general, the blends containing 5% ethanol had very close fuel properties compared to diesel fuel. Ali et al. [25, 26] used 12 different blends of methyl tallowate, methyl soyate, ethanol, and diesel fuel in a diesel engine and found that engine performance with these blends did not differ significantly from that with diesel fuel. Violeta Makareviciene et al. [27] conducted solubility test on multi-component biodiesel fuel system. They found that rapeseed oil ethyl and methyl esters are soluble in ethanol and diesel without limits and the addition of ethanol increases the inter-solubility of ethanol and fossil diesel. Prommes kwanchearon et al. [28] conducted solubility test on EB-diesel blend using palm oil methyl ester as additive and reported emission test results of the fuel blend. They found that 5% ethanol, 15% Biodiesel and 20% diesel blend was most suitable for diesohol production due to its lower emissions and acceptable fuel properties.

Through the above literature review, it can be concluded that there are many technical barriers to the direct use of ethanol in diesel fuel, due to the differences in its physical and chemical properties: for instance, the solubility of ethanol in diesel fuel. In addition, the research results on the engine performance are contradictory. Therefore, further studies are necessary to find the way to make ethanol be mixable with diesel and then applicable to diesel engines. The objective of this study is to investigate the solubility of diesel with ethanol as well as the use of biodiesel (waste frying oil methyl esters) as an additive in stabilizing ethanol in diesel fuel blends and to conduct experiments on the diesel engine performance when fuelled with diesel-biodiesel-ethanol fuel blends compared with that fuelled with pure diesel.

## 2. Experimental study

The experimental study was carried out in two stages:

- To investigate the phase stability of ED and EB-diesel blends.
- And to conduct tests on engine performance when operating alternately on diesel fuel and its various blends with ethanol and biodiesel.

### 2.1. Fuel used:

Diesel, ethanol and biodiesel were used as the materials to form the fuel blends. Diesel fuel was obtained from the local fuels supply station, and the ethanol with a purity of 99% (Assay, UK) was purchased from a shop selling chemicals. Biodiesel fuel was produced from waste frying oil by transesterification process using methanol as the alcohol and sodium hydroxide (NaOH) as the catalyst. Methanol and NaOH both with a purity of 99% (Assay, UK) were obtained from the same place where the ethanol was purchased. The transesterification reaction was carried out with methanol/oil molar ratio of 4.5:1 and catalyst concentration of 0.5% (wt /wt. of oil) NaOH. The procedures as follows: waste frying oil was heated to 110 °C to evaporate possibly existed water in the oil and then filtered. Then the oil was poured in to (preheated to 70 °C) vessel placed on, a temperature-controlled, hotplate magnetic stirrer. With the oil stirred and heated to a temperature of 50 °C, a solution of methanol and sodium hydroxide (prepared freshly during the experiment) was added into the vessel taking this moment as time zero of the reaction. After a 30 minute reaction time, the mixture was transfer red to a separating flask and allowed to settle for overnight to produce two distinct liquid phases (i.e. methyl ester-upper layer and glycerin - lower layer). After separation of the two phases by sedimentation, the methyl esters were purified by distilling the residual methanol at 80 °C. The residual catalyst was extracted by the successive washing of the methyl ester with warm distilled water at a temperature of 50°C until the wash water becomes clear Then, the water present was removed by heating at 110 °C and the final product, biodiesel, would be obtained as a clear, light yellow liquid. Finally, the fatty acid (FA) composition of the obtained waste frying methyl ester i.e. biodiesel was determined using High Pressure Gas Chromatography (GC) model 2010 equipped with a split injector(AOC-20i), a flame ionization detector (FID) and a DB-23(60m length, 0.25mm I.D., 0.15 um film thickness) column with maximum temperature of 260°C [29]. The operational conditions for GC were as follows: the starting temperature was 165°C and this temperature was retained for 8 min; then the temperature was increased to 185°C with a rate of 1°C /min; and then increased to 220°C with a rate of 5°C /min, staying at 220°C for 10 min. The injector and detector temperatures were set at 230°C and 240°C, respectively, and helium was used as carrier gas at a flow rate of 1.20 mL/min. The relative percentage of the FA was calculated on the basis of the peak area of a fatty acid species to the total peak area of all the fatty acids in the sample. Each FA determination was run in triplicate, and average values are reported (Table 1).

Table 1: Fatty acid composition (wt %) of the biodiesel (waste frying oil methyl esters).

Fatty acid methyl ester				Molecular mass, (kg kmol <sup>-1</sup> )		Percent contribution of element,%		
Trivial name	Chemical formulae	Symbol	%,by weight	Fatty acid	Contrib- ution	C	H	O
Myristic	C <sub>14</sub> H <sub>28</sub> O <sub>2</sub>	C14:0	0.06	228.38	0.14	73.63	12.36	14.01
Palmitic	C <sub>16</sub> H <sub>32</sub> O <sub>2</sub>	C16:0	8.51	256.43	21.82	74.94	12.58	12.48
Palmitoleic	C <sub>16</sub> H <sub>30</sub> O <sub>2</sub>	C16:1	0.18	254.41	0.46	75.54	11.89	12.58
Heptadecanoic	C <sub>17</sub> H <sub>34</sub> O <sub>2</sub>	C17:0	0.06	270.46	0.16	75.50	12.67	11.83
Heptadecenoic	C <sub>17</sub> H <sub>32</sub> O <sub>2</sub>	C17:1	0.03	268.44	0.08	76.06	12.02	11.92
Stearic	C <sub>18</sub> H <sub>36</sub> O <sub>2</sub>	C18:0	3.47	284.48	9.87	76.00	12.76	11.25
Oleic	C <sub>18</sub> H <sub>34</sub> O <sub>2</sub>	C18:1	27.91	282.47	78.84	76.54	12.13	11.33
Linoleic	C <sub>18</sub> H <sub>32</sub> O <sub>2</sub>	C18:2	57.98	280.45	162.61	77.09	11.50	11.41
Linolenic	C <sub>18</sub> H <sub>30</sub> O <sub>2</sub>	C18:3	0.56	278.44	1.56	77.65	10.86	11.49
Arachidic	C <sub>20</sub> H <sub>40</sub> O <sub>2</sub>	C20:0	0.33	312.54	1.03	76.86	12.90	10.24
Gadoleic	C <sub>20</sub> H <sub>38</sub> O <sub>2</sub>	C20:1	0.18	310.52	0.56	77.36	12.34	10.30
Erucic	C <sub>22</sub> H <sub>42</sub> O <sub>2</sub>	C22:0	0.52	338.58	1.76	78.04	12.50	9.45
Lignoceric	C <sub>24</sub> H <sub>48</sub> O <sub>2</sub>	C24:0	0.21	368.65	0.77	78.20	13.12	8.68
Average value				279.66		76.42	12.28	11.31

## 2.2. Phase stability:

The experiments on solubility were performed on two stages: Firstly, ethanol- diesel blends with (% , v/v) 5, 10, 15 and 20 of ethanol with 95, 90, 85 and 80 of diesel, respectively, which were named as DE5, DE10, DE15 and DE20. Secondly, ethanol- biodiesel- diesel blends with (% , v/v) 5, 10, 15 and 20 of ethanol, 85, 80, 75 and 70 of diesel respectively, and with a fixed 10 % volume of biodiesel as a co-solvent, which were named as DBE5, DBE10, DBE15 and DBE20. The fuels with a predetermined volume were mixed into a homogeneous mixture by a magnetic stirrer for five minutes. Then, the final blend was kept in a graduated glass vial for observing the solubility and the physical stability.

## 2.3. Engine tests:

Tests have been conducted on a naturally aspirated, single cylinder, four stroke diesel engine type Lister 8-1 TE 9. The experimental set up is shown in Fig.1. The engine swept volume was 1433-cm<sup>3</sup>; the maximum power of 8-HP (6-kW). The engine was coupled to a three phase asynchronous electrical AC dynamometer (type B.K.B. Compound), which can be used for absorbing the power developed by the engine and as a motor for starting the engine. The dynamometer maximum speed is 2500 rpm; and the torque arm radius is 220-mm. The load in Newton and speed in rpm can be measured directly. The volumetric fuel consumption was measured by a glass tube divided into three sections 25, 50, and 75 cm<sup>3</sup>. and the volumetric air consumption was determined by the air consumption meter type TE 40 equipped with air tank fitted with a circular sharp-edge measuring orifice of 32.02-mm in diameter with a discharge coefficient of 0.6 and with an inclined manometer capable of reading 1-mm H<sub>2</sub>O to measure the pressure drop across the orifice. The time of 25-cm<sup>3</sup> fuel and air consumption (during this time) were measured with a stopwatch with accuracy of ± 0.01 s.

The experiments on engine performance were carried out by using pure diesel fuel and four fuel blends at

various engine-operating conditions. The fuel blends were prepared, just before starting the experiment, by pouring ethanol and biodiesel into a fuel measuring tank in the following proportions (% by volume): D85B10E5, D80B10E10, D75B10E15 and D70B10E20 and mixed together by hand in order to keep fuel blends prepared in homogeneous conditions. To obtain the baseline parameters, the engine was first operated on pure diesel fuel. The engine performance was taken at constant load and at engine speed ranges from 800 to and 1600 rpm with an increment of 200-rpm. Similar experiments with a fuel blends were conducted over the same engine load and speeds without any modification to the engine. The start of measurements were taken after the engine was warmed-up and the required speed was obtained by changing the rack position of the high pressure diesel fuel pump. The operating conditions were stabilized and the variables that were continuously measured were recorded. This included the dynamometer speed and load, time required to consume 25-cm<sup>3</sup> of fuels, pressure drop across the orifice. Consequently, the engine torque, brake power, brake specific fuel consumption, brake thermal efficiency, actual air fuel ratio (AFR), and the equivalence AFR for the tested fuels were calculated. For all conducted experiments, before running the engine to a new fuel blend, it was allowed to run for sufficient time to consume the remaining fuel from the previous experiment. For each experiment, three runs were performed to obtain an average value of the experimental data.

## 3. Results and Discussion

### 3.1. Fuel properties:

The ultimate analysis was performed on biodiesel to determine the fatty acid methyl ester compositions and accordingly to calculate its elemental composition. Based on that analysis, as shown in table1, the elemental composition of the biodiesel consists of 76.4 wt % carbon, 12.3 wt % hydrogen and 11.3 wt % oxygen. Moreover, the calculated average chemical formula is C<sub>17.4</sub> H<sub>33.4</sub> O<sub>1.9</sub>. In addition, the Cetane number (CN) of the biodiesel was

calculated based on the CN of the fatty acid methyl esters as shown in Tab.2, [30]. Knowing the elemental composition of the fuels used for the experiment, the Stoichiometric air-fuel ratio and the lower heating value of the fuels and fuel blends can be determined using the following equations [31 and 32]:

$$C_a H_b O + c(O_2 + 3.776N_2) = d CO_2 + e H_2O + c(3.776N_2) \quad (1)$$

$$LHV = 33.9C + 125.6H - 10.9(O_y - S) - 2.512(9H + W) \quad (2)$$

$$(LHV)_{bl} = \sum \chi_i \rho_i LHV_i / \sum \chi_i \rho_i \quad (3)$$

$$(AFR)_{bl} = \sum \chi_i \rho_i (AFR)_{st} / \sum \chi_i \rho_i \quad (4)$$

$$\rho_{bl} = \chi_i \rho_i \quad (5)$$

Based upon the ratio from Eq.1, the molecular weights of oxygen, atmospheric nitrogen, atomic carbon, and atomic hydrogen are, 15.9994, 28.16, 12.011, and 1.008, respectively. In Eq.2, C, H, O<sub>y</sub> and W represent the elemental composition of fuels i.e. the amounts of carbon, hydrogen, oxygen and water in unit mass of the fuel,  $\chi_i$  the volumetric percentage of fuel constituent i,  $\rho_i$  is the constituent i fuel density. The computation value of Stoichiometric air-fuel ratios and lower heating values of diesel, ethanol, biodiesel, and its blends are presented in Table 3. As shown from Tab. 3 ethanol has a lower cetane number than diesel fuel, and therefore the ignition delay could increase. However, the large cetane number of the biodiesel compensates, in some extent, the reduction of cetane number from addition of ethanol to diesel, thus improving the engine ignition. The lower heating value of

the ethanol and biodiesel are lower than that of diesel fuel, and consequently the amounts of ethanol and biodiesel should be 1.56 and 1.14, respectively times greater than that of diesel fuel to achieve the same power output. The stoichiometric air-fuel ratio of the ethanol and biodiesel were 62% and 86%, respectively of the diesel fuel, hence the amount of air required for complete combustion is lesser. The latent heat of vaporization of the ethanol and biodiesel was 2.24 times greater than that of diesel fuel. This means that the temperature of the air-fuel mixture in the engine cylinder at the end of the compression stroke decreases (the time interval between the beginning and the end of ignition) and as a result the combustion temperature decreases. In addition, blending ethanol and biodiesel with diesel fuel can supply additional oxygen for diffusive controlled combustion phase and can cause improvements in the combustion process.

### 3.2. Solubility of the blends of diesel with ethanol:

The test results of the solubility of ethanol-diesel and ethanol – diesel with biodiesel as a co-solvent are shown in Figs. 2A and 2B respectively. From Fig. 2A it can be seen that the blends of ethanol with diesel were not stable and were all separated after some times. DE5, DE10, DE15 and DE20 maintained 80, 24, 5, and 2 hours, respectively, before separating. Therefore, to solve this problem, biodiesel was used as a co-solvent of ethanol in diesel fuel for further tests. The results show that all of the blends with biodiesel were all lasted longer before the separation happened. Fig. 2B shows that the blends of DBE10, DBE15 and DBE20 were separated after 9, 3 and 1 days, respectively. Whereas the blend of DBE5 was of the best stability with very little separation.

Table 3: Chemical and physical properties of the tested fuels

Property	Diesel	Biodiesel	Ethanol	DBE5	DBE10	DBE15	DBE20
Chemical formulae	C <sub>12.35</sub> H <sub>21.76</sub>	C <sub>17.4</sub> H <sub>33.4</sub> O <sub>1.9</sub>	C <sub>2</sub> H <sub>5</sub> OH	--	--	--	--
Elemental composition, w%:							
C	87.13	76.40	52.14	--	--	--	--
H	12.88	12.23	13.13	--	--	--	--
O	0	11.30	34.73	--	--	--	--
Density @20 °C	820	882	786	824.5	822.8	821.1	819.4
Viscosity @ 20 °C, Pa s	2.8	4.6	1.20	--	--	--	--
Latent heat, kJ kg <sup>-1</sup>	375	--	840	--	--	--	--
Cetane number	48	49.30	6	--	--	--	--
Lower heating value, MJ kg <sup>-1</sup>	42.90	37.40	27.47	41.58	40.84	40.10	39.35
Stoichiometric AFR	14.45	12.48	9.0	13.98	13.72	13.46	13.19

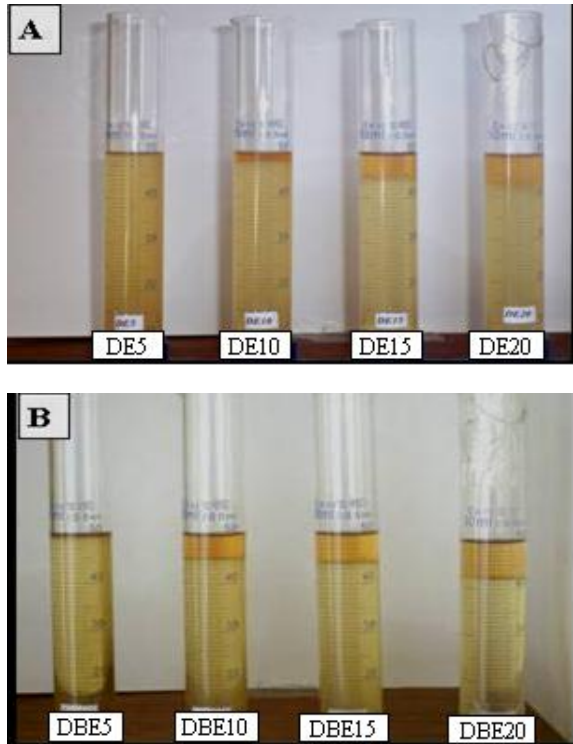


Figure 2: Solubility of the blends of ethanol with diesel: A - DE, B - DBE.

### 3.3. Engine performance:

For each testing condition, the volumetric fuel flow rate was measured, and then converted into the mass consumption rate based on the density of the fuels tested. Based on the engine torque, the engine speed and the mass consumption rate of the fuel and air, the actual air–fuel ratio, the brake power, the brake specific fuel consumption (BSFC) and the brake thermal efficiency (BTE) can be calculated.

#### 3.3.1. Effect of fuel blends on equivalence air–fuel ratio:

The equivalence air–fuel ratio ( $\phi$ ) was calculated based on the actual air–fuel ratio and stoichiometric air–fuel ratio. The variation of the  $\phi$  of diesel fuel and fuel blends as a function of the engine speed is shown in Fig.3. As shown from the figure the  $\phi$  increases as the engine speed increase and then decrease for all fuel tested, this is due to the engine friction resistance at low speeds (up to 1400 rpm) and to the hydraulic losses in the intake system at higher speeds. In addition, it is obvious that the  $\phi$  of the fuel blends is higher than diesel fuel. This can be attributed to the fact that at each engine speed, the amount of air enter to the engine is constant. Moreover, to obtain the same equivalence air–fuel ratio, we need more mass flow rate of fuel blends than diesel fuel, because the stoichiometric air–fuel ratio of ethanol and biodiesel is lower than diesel fuel. Accordingly, as the ethanol percentage increases in the blends the equivalence AFR increases.

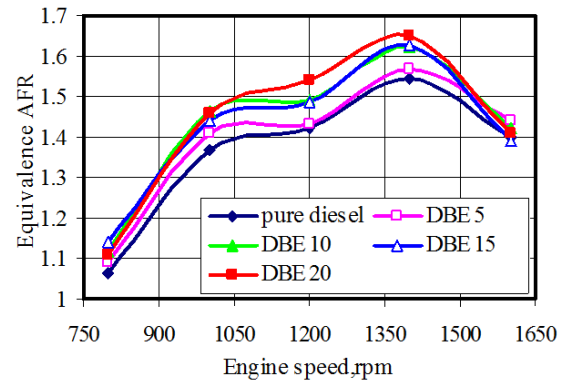


Figure 3: The variation of equivalence air–fuel ratio with different engine speeds for DBE blends and pure diesel fuel.

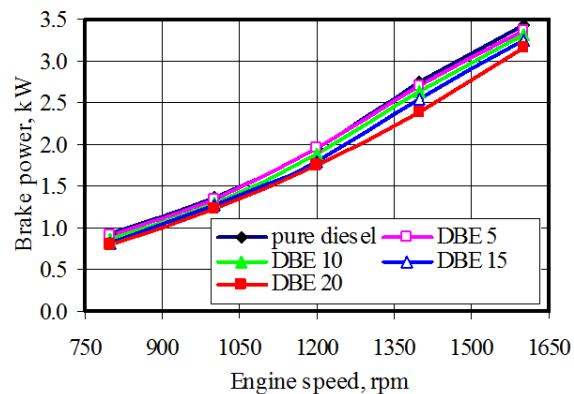


Figure 4: The variation of brake power with different engine speeds for DBE blends and pure diesel fuel.

#### 3.3.2. Effect of fuel blends on engine brake power:

The variation of the engine brake power obtained with different fuel blends at various engine speeds is shown in Fig. 4. As the figure shows the engine power increases with the increasing of the engine speed for all fuels. Comparing with diesel fuel, the blend including 5% ethanol (DBE5) gives the same engine power. However, as the ethanol concentration increases above 5% the engine power decreases. This can be explained as follows: for a small amount of ethanol, the large cetane number of the biodiesel compensates the reduction of cetane number from addition of ethanol to diesel fuel. Therefore, the heat of combustion and the cetane number of the DBE5 blend remained steady, and thus the engine power remains the same as the engine operates with pure diesel fuel. On the other hand, as the ethanol concentration increases the cetane number of the blended fuel decreases and the auto ignition temperature and heat of vaporization (the latent heat of vaporization of ethanol is higher than diesel fuel) of blended fuels increases. Therefore, longer ignition delays occur and the combustion process may extend to the expansion stroke and the fuel cannot be completely burned as results the engine power decrease. Another reason for decreasing engine power can be related to the decreasing lower heating value of DBE blends due the lower heating value of the ethanol and biodiesel than that of diesel fuel.

### 3.3.3. Effect of fuel blends on brake specific fuel consumption:

The brake specific fuel consumption variation of the tested fuels at various engine speeds is shown in Fig. 5. It is obvious that the BSFC decreases with the increasing of engine speeds up to 1400 rpm, but increases after 1400 rpm. The minimum BSFC lies between the engine speeds of 1200 to 1400 rpm for all fuel tested. In addition, it can be seen that the BSFC of fuel blends are higher than that of diesel fuel, and increases with the increase of ethanol concentration in the blends. This is because the lower heating value of ethanol and biodiesel is lower than that of diesel fuel. Therefore, more fuel is required to obtain the same engine brake power.

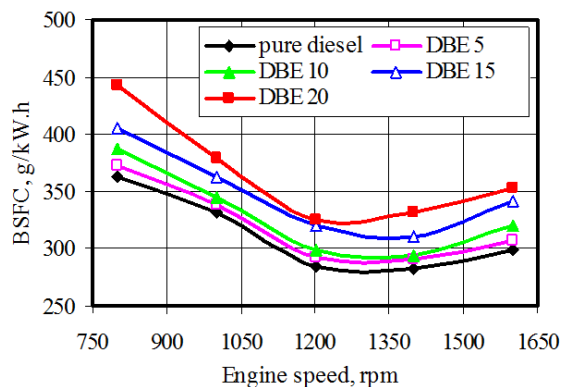


Figure 5: The variation of brake specific fuel consumption with different engine speeds for DBE blends and pure diesel fuel.

### 3.3.4. Effect of fuel blends on brake thermal efficiency:

The variation of brake thermal efficiency with engine speed for different fuels is shown in Fig. 6. The BTE increases with the increase of engine speed from 800 to 1400 rpm but decreases from 1400 to 1600 rpm. Compared with diesel fuel, the BTE of the DBE5 and DBE10 blends is slightly higher than that of diesel fuel. However, as the ethanol concentration increases above 10% the BTE decrease. This can be attributed to the following factors: Up to 10% ethanol concentration, the oxygen content in the fuel blends improves combustion especially during the phase of diffusion-controlled combustion and hence increases the BTE. Higher than 10% ethanol concentration, the higher latent heat of vaporization leads to increase the heat losses; the lower cetane number leads to longer ignition delay and hence incomplete combustion occur as more fuel is burned in the expansion stroke; and the reduction in lower heating value of the fuel blends leads to an increase in the volume of fuel injected to maintain the same engine power. Therefore, the combined effect of these factors will lead to the BTE decrease.

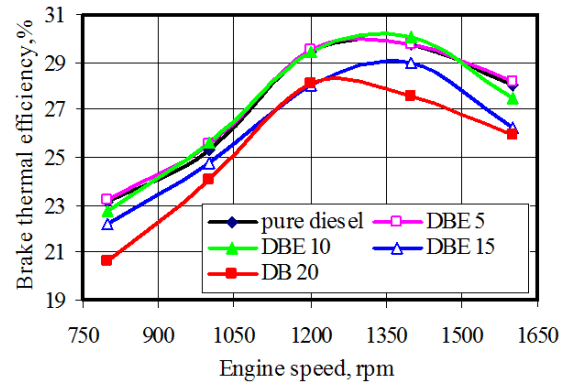


Figure 6: The variation of brake thermal efficiency with different engine speeds for DBE blends and pure diesel fuel.

## 4. Conclusion

An experimental study on the phase stability of ethanol-diesel and ethanol-diesel blended with a fixed amount of biodiesel as a co-solvent of ethanol in diesel fuel as well as the effect of ethanol-diesel-biodiesel blends on engine performance, and compared to the base diesel fuel had been investigated. The main results obtained can be summarized as follows:

- Waste frying oil-derived biodiesel could be used as an effective additive for diesel-ethanol mixture. The addition of biodiesel to diesel-ethanol mixture permits a higher ethanol concentration and contributes to more stable fuel blends than a mixture of only diesel-ethanol blends.
- The inter-solubility of the components of diesel-biodiesel-ethanol system decreased with increasing ethanol concentration. The blend of DBE5 was of the best stability with very little separation.
- Experimental results show that equivalence air-fuel ratio increases as the percentage of ethanol (% v) in the blended fuel increases.
- The engine brake power of fuel blend of DBE5 was very close to that of diesel fuel, but for higher ethanol concentration in the blends it was slightly lower compared with diesel fuel.
- The brake specific fuel consumption of the engine fuelled by the blends was higher compared with pure diesel. The more ethanol was added in, the higher brake specific fuel consumption was.
- The brake thermal efficiency of the engine fuelled with the DBE5% and DBE10% blends were higher but decreases as the ethanol concentrations increased compared with diesel fuel.
- In general, it can be concluded that ethanol can be used in compression ignition engines without any modification on the engine design by blending it with diesel fuel at low concentration. The phase separation which is the most important problem encountered can be prevented by adding biodiesel into the blends. The optimum percentage of ethanol was determined as 5% with 85 % diesel and 10% of biodiesel.

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