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Technical note

Physico-chemical properties of ethanol–diesel blend fuel and its effect on performance and emissions of diesel engines

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Abstract

The effects of different ethanol–diesel blended fuels on the performance and emissions of diesel engines have been evaluated experimentally and compared in this paper. The purpose of this project is to find the optimum percentage of ethanol that gives simultaneously better performance and lower emissions. The experiments were conducted on a water-cooled single-cylinder Direct Injection (DI) diesel engine using 0% (neat diesel fuel), 5% (E5–D), 10% (E10–D), 15% (E15–D), and 20% (E20–D) ethanol–diesel blended fuels. With the same rated power for different blended fuels and pure diesel fuel, the engine performance parameters (including power, torque, fuel consumption, and exhaust temperature) and exhaust emissions [Bosch smoke number, CO, NO_x, total hydrocarbon (THC)] were measured. The results indicate that: the brake specific fuel consumption and brake thermal efficiency increased with an increase of ethanol contents in the blended fuel at overall operating conditions; smoke emissions decreased with ethanol–diesel blended fuel, especially with E10–D and E15–D. CO and NO_x emissions reduced for ethanol–diesel blends, but THC increased significantly when compared to neat diesel fuel.

1. Introduction

Diesel engines have been widely used as engineering machinery, automobile, and shipping power equipment due to their excellent drivability and economy. At the same

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time, diesel engines are major contributors of various types of air pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter (PM), and other harmful compounds. With the increasing concern of the environment and more stringent government regulation on exhaust emissions, the reduction in engine emissions is a major research objective in engine development. It is difficult to reduce PM and NO_x simultaneously owing to the trade-off between NO_x and PM [1].

Ethanol is a renewable energy, it can be made from many raw materials such as sugar cane, molasses, cassava, waste biomass materials, sorghum, corn, barley, sugar beets, etc. by using already improved and demonstrated technologies [2,3]. The objective of this work was to find the maximum possible and optimum replacement of diesel fuel by ethanol and compare the performance of diesel engine fueled with ethanol–diesel blended fuels [4]. Towards this end, an experimental study was carried out to test the performance of various ethanol–diesel fuel mixtures; the content of ethanol is 0, 5, 10, 15, and 20% by volume, respectively [5]. The tests were run at rated speed and maximum torque speed and five torques including 25, 50, 75, 90%, and full load for each engine speed. Gas emissions for 10, 15% ethanol–diesel blended fuels and diesel fuel were measured at rated speed and maximum torque speed.

2. Fuel properties

The ethanol used in the tests was limited to essentially anhydrous ethanol because other kinds of ethanol are not soluble or have very limited solubility in the vast majority of diesel fuels. The solubility of ethanol in diesel fuel is dependent on the hydrocarbon composition, wax content and ambient temperature of the diesel fuel. This solubility is also dependent on the water content of the blend fuels. To overcome this problem, a solubilizer is indispensable in ethanol–diesel blended fuel.

Commercial diesel fuel and analysis-grade anhydrous ethanol (99.7% purity) were used in this test. The compound of ethanol–diesel blends involves solubilizer dosage, ethanol, and diesel fuel. The blending protocol was to first mix the solubilizer (1.5% v/v for all ethanol–diesel blends except for pure diesel fuel) with ethanol, and then blend this mixture into the diesel fuel. For example, 15% ethanol–diesel blend (E15–D) consists of 1.5% solubilizer, 15% ethanol, and 83.5% diesel.

The presence of ethanol generates different physico-chemical modifications of the diesel fuel, notably reductions of cetane number, low heat content, viscosity, flashpoint, and pour point, etc. These modifications change the spray characteristics, combustion performance, and engine emissions. We investigated some of these blended fuels parameters as follows (Table 1).

2.1. Cetane number

The cetane number is an important fuel property for diesel engines. It has an influence on engine start-ability, emissions, peak cylinder pressure and combustion noise. A high cetane number ensures good cold starting ability, low noise and long engine life. Cetane numbers of blended fuel depend on the amount and type of additive used in the blends.

Table 1
Physical and chemical properties of diesel and anhydrous ethanol

	Formula	Mole weight	Density at 20 °C ($\times 10^3$ kg/m^2)	Boiling point (°C)	Pour point (°C)	Flash-point (°C)	Vis-cosity (mPa s)	Heat content (MJ/kg)	CN
Diesel	C_xH_y	190–220	0.829	180–360	−1 to 3	65–88	3.35	42.5	45–50
Ethanol	CH_3-CH_2OH	46.07	0.789	78.4	−117.3	13–14	1.20	26.8	5–8

Cetane numbers can be measured through the engine CFR. Since the cetane number of ethanol is extremely low, the cetane number of the ethanol–diesel blend fuel reduces significantly. According to research carried out by Corkwell, each 10-vol% ethanol added to the diesel fuel, results in a 7.1-unit reduction in cetane number of the resulting blend.

2.2. Lubricity and viscosity

Lubricity is a potential problem with oxygenated blended fuels. Fuel viscosity and lubricity characteristics play significant roles in the lubrication of fuel systems, particularly those incorporating rotary distributor injection pumps that rely fully on the fuel for lubrication within the high-pressure mechanism. Lower fuel viscosities lead to greater pump and injector leakage, which reduces maximum fuel delivery and power output. The lubricity properties of diesel fuels are generally evaluated by the use of a bench test described as the High Frequency Reciprocating Rig (HFRR). The test measures the wear scar of a test specimen that is subjected to wear, using only the test fuel as lubricant.

Lubricity is mainly governed by the kinematic viscosity. Kinematic viscosity can be measured easily. Fig. 1 shows the experimental results of blend fuels. As shown in Fig. 1, the addition of ethanol to diesel lowers fuel viscosity. With an ethanol contents of 10–20%, the viscosity does not reach the minimum requirements for diesel fuels.

2.3. Energy density

The low heat value of a fuel has a direct influence on the power output of the engine. Ethanol contains about 33% lesser energy than that for diesel fuel on a mass basis. Blending ethanol with diesel lowers the volumetric energy density of the fuel in proportion to the ethanol content.

2.4. Flash point

The flash point is the lowest temperature at which a fuel will ignite when exposed to an ignition source. The flashpoint of the fuel affects the shipping and storage classification of fuels and the precautions that should be used in handling and transporting the fuel. In

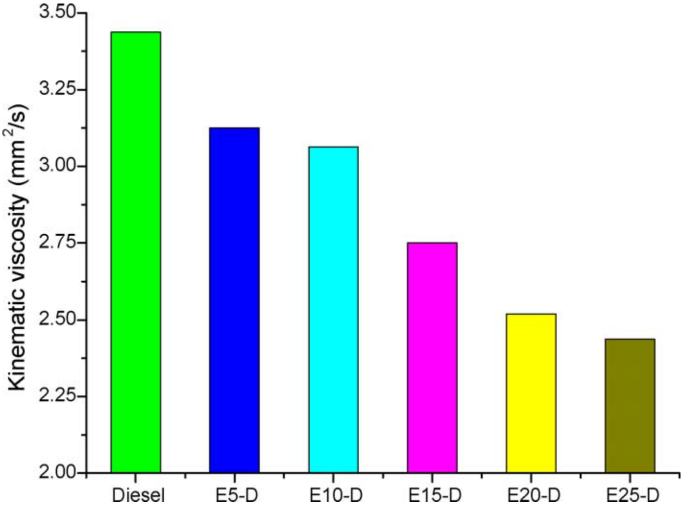

Fig. 1. Kinematic viscosities of blend fuels and diesel fuel.

general, flash point measurements are typically dominated by the fuel component in the blend with the lowest flash point. This can be verified in Fig. 2. The flashpoint of ethanol–diesel blend fuels is mainly dominated by ethanol.

2.5. Surface tension

Surface tensions affects the spray characteristics and atomization of fuel droplets; these lead to significant effect on combustion efficiency. Surface tensions were measured with

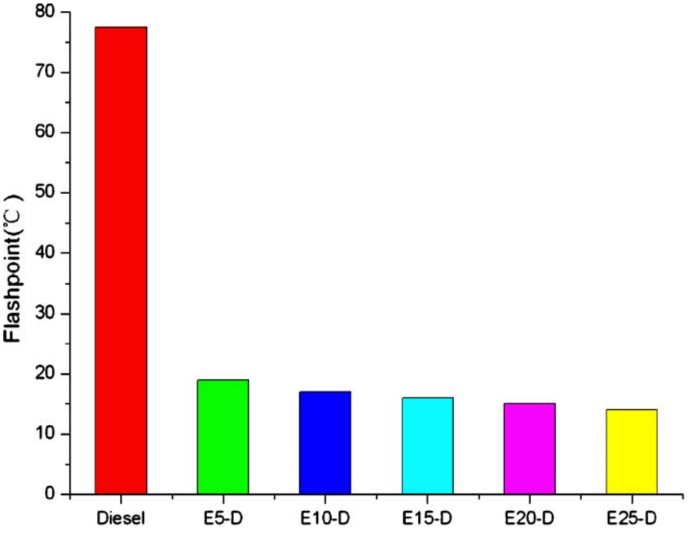

Fig. 2. Flash points of blend fuels and diesel fuel.

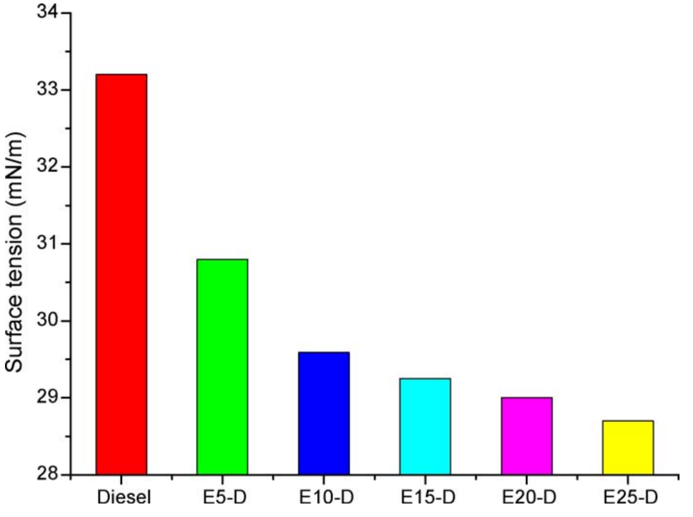

Fig. 3. Surface tensions of blend fuels and diesel fuel.

an automatic stabilizer tension-meter as well as with an experimental method. The results are shown in Fig. 3.

2.6. Boiling point

The boiling point of ethanol is below the lowest boiling fraction of normal diesel fuel. The addition of ethanol modifies the shape of distillation curve at temperatures below 200 °C.

2.7. Stability and phase separation

Phase separation and water tolerance of ethanol–diesel blend fuel is a well-known concern. Fuel instability is an obvious problem when full phase separation has occurred. Thus, water tolerance of the ethanol/diesel blends was determined by blending additional water into samples of the mixtures. As expected, ethanol–diesel blend fuel samples at higher temperature are more readily able to tolerate greater amounts of water contamination. Low temperatures and high water contamination are more likely to advance the start of fuel instability and phase separation.

Under most conditions, ethanol readily blends with gasoline at all ratios. Unlike gasoline, diesel fuel is not easily blended with ethanol under all conditions. Particularly troublesome are conditions of low temperature and/or water contamination. Both can result in fuel instability due to phase separation.

3. Engine tests and results

The test engine is a water-cooled single-cylinder Direct Injection (DI) diesel engine. The ZS1100 model has a bore $\times$ stroke of $100\times115\ \text{mm}^2$ and a compression ratio of

17.5:1. The engine is rated at 12.1 kW power at a speed of 2200 rpm, the maximum torque is 58.9 N m at a speed of 1760 rpm.

The engine performance and emissions at various loads under different engine speeds (2200 and 1760 rpm) using ethanol–diesel blend fuels and neat diesel was measured in terms of brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), smoke opacity, carbon monoxide (CO), oxides of nitrogen (NO_x), and total hydrocarbon (THC). The results are shown below.

3.1. Effect of ethanol content on BSFC

Fig. 4 shows the BSFC of different blended fuels at various loads at 2200 and 1760 rpm. It is obvious that the BSFC decreases with the increasing of load at 2200 rpm, but slightly increases after 75% load at 1760 rpm.

In general, the BSFC increased with increasing ethanol content in blend fuel. This is due to the fact that the low heat value of ethanol is about 2/3 of that of diesel. The second explanation, which has been offered for the remarkable increase at low load, is the incomplete combustion due to the ignition delay of ethanol–diesel blend fuel.

3.2. Effect of ethanol content on brake thermal efficiency

From the experimental results, the engine brake thermal efficiency (BTE) can be calculated from the BSFC and low heat value of the blend fuel. The calculated results are presented in Fig. 5. It can be seen from Fig. 5 that the BTE was improved for all engine conditions (except E15–D at 25% load at 2200 rpm) fueled with ethanol–diesel blend fuels, and the BTE improved more with the increasing ethanol content in blend fuels at the same operation condition.

In general, the engine BTE can be improved by means of adding ethanol fuel (oxygenated fuel) to diesel. This can be explained for the following reasons: the quality of the spray with blend fuels was improved since the boiling point of ethanol is lower than that of diesel; the combustion is more complete in the fuel-rich zone

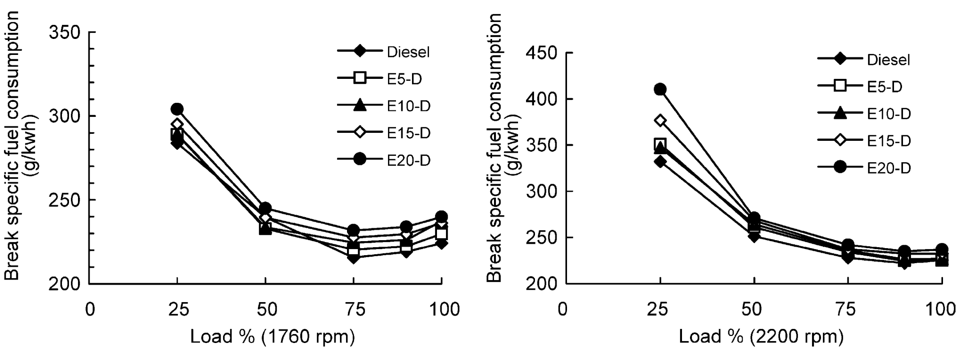

Fig. 4. Break specific fuel consumption of the engine using different blend fuels under various operating conditions.

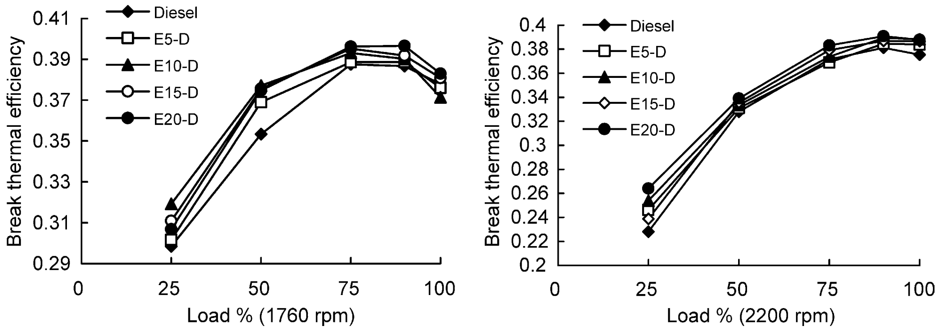

Fig. 5. Brake thermal efficiency of the engine using different blended fuels under various operating conditions.

due to the oxygenate of ethanol, so that the combustion efficiency is enhanced; heat losses decrease in the cylinder due to lower flame temperature of ethanol than that of diesel.

3.3. Effect of ethanol content on smoke emission

The Bosch smoke number was measured for all five fuels (ethanol–diesel blend fuels and diesel) with the engine at various loads at 2200 and 1760 rpm. Smoke opacity for E15–D and E20–D increased at low and medium loads (25 and 50%) but decreased at large and full load (75, 90, and 100%) for E5–D and E10–D at 2200 rpm. At 1760 rpm, the smoke opacity is very low from 25% load to 90% load for blend fuels and neat diesel, but very high at full load. Smoke opacity decreased for ethanol–diesel blend fuels at full load at 1760 rpm.

3.4. Effect of ethanol content on gas pollutant emissions

Based on the above analysis in terms of BSFC, BTE, and smoke opacity for different ethanol blended fuels and diesel fuel, we found that the smoke opacity increased at low and medium loads at 2200 rpm for E5–D, the BSFC increased dramatically at various operating condition for E20–D, so that E5–D and E20–D are not the optimum blend fuels for a diesel engine. Thus, we measured the gas pollutant emissions only for E10–D and E15–D, and compared them to those for the baseline diesel (Fig. 6).

The regulated emissions of THC, CO, and NO_x were measured using the baseline diesel and blend fuels (E10–D and E15–D) cases. The Chinese emission standard for single-cylinder diesel engine—8-mode test cycle was used for the tests. An AVL CEB gas analyzer was used to measure the gas emissions. The modes are: four torques at rated speed (10, 50, 75, and 100% loads, respectively), three torques at rated torque speed (50, 75, and 100% loads, respectively), and one at idle speed. The results are presented in Table 2.

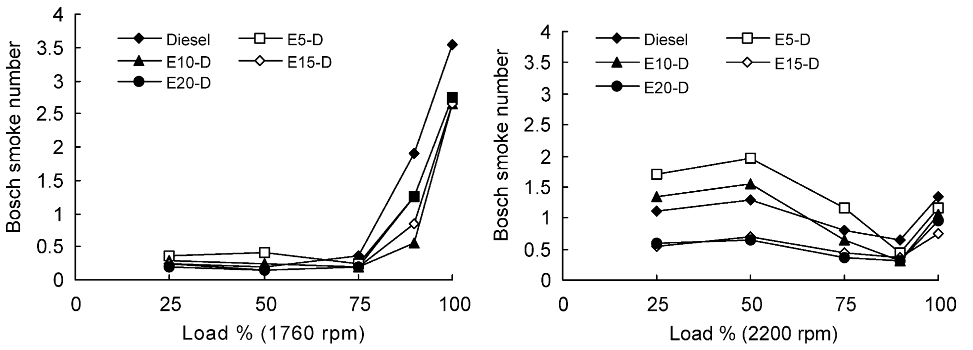

Fig. 6. The relationship between smoke and ethanol content in blend fuels under various operating conditions.

It can be seen from Table 2 that both the CO and NO_x reduced with the ethanol–diesel blend fuels compared to neat diesel, but the THC increased dramatically. In order to understand the effect of ethanol on gas emissions in detail, the author analyzed the emission characteristics at the main operating conditions.

CO emissions at various loads under rated engine speed are presented in Fig. 7. At rated speed, CO emissions increased at low and medium loads (10 and 50% load, respectively) for E10–D and E15–D. At high and full loads (75 and 100% loads, respectively) at rated speed, the CO emissions decreased significantly with the increase of load for the ethanol–diesel blended fuels. At full load, CO decreased by 49 and 29% for E10–D and E15–D, respectively.

The NO_x emissions of the engine using different blended fuels and neat diesel under various operating conditions are shown in Fig. 8. It can be seen that the general tendency of engine NO_x emissions is opposite to that for CO. For an engine speed of 2200 rpm, both ethanol–diesel blended fuels reduced the NO_x emissions about 50 and 32–35% at low and medium load, respectively, but reduced only slightly at 75% load. At full load, NO_x emissions are higher for blended fuels than neat diesel fuel.

Table 2
Engine emissions of blend fuels and diesel fuel

	CO		NO_x		THC	
	Result (g/kW h)	Changed (%)	Result (g/kW h)	Changed (%)	Result (g/kW h)	Changed (%)
Diesel	5.32	–	10.04	–	0.97	–
E10–D	4.46	−16.7	9.81	−2.3	1.41	+45.4
E15–D	5.01	−5.8	9.62	−4.2	1.37	+41.2

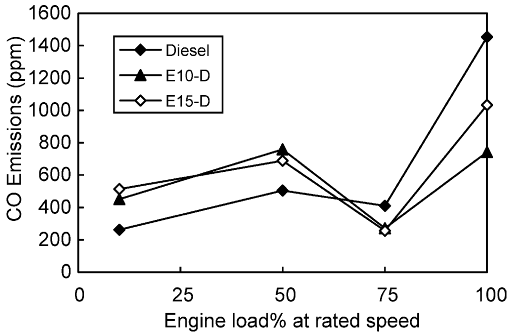

Fig. 7. CO emissions versus engine load with ethanol–diesel blend fuels and diesel.

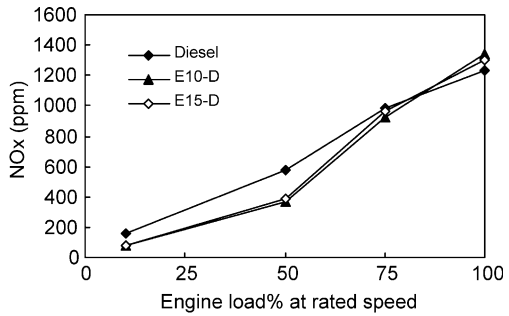

Fig. 8. NO_x emissions versus engine load with neat diesel and ethanol–diesel blend fuels.

Fig. 9 shows the effect of ethanol on THC production. We found that with the introduction of ethanol in diesel fuel, the THC emissions increased dramatically at various engine conditions. Furthermore, THC increased more for E10–D than for E15–D at various operating conditions (except for 10% load at 2200 rpm).

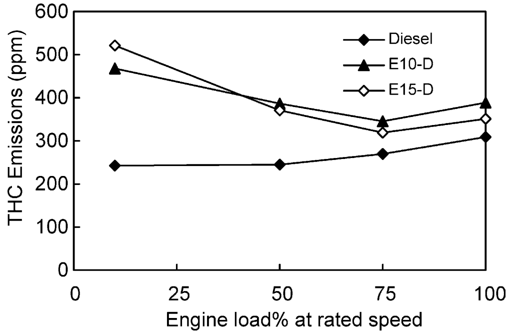

Fig. 9. Total hydrocarbon emissions versus engine load with neat diesel and ethanol–diesel blend fuels.

4. Conclusions

This work was undertaken to study and compare the effects of different content of ethanol–diesel blend fuels on BSFC, BTE, and exhaust emissions (smoke number, CO, NO_x, and THC) and the following conclusions can be obtained from the study:

1. The BSFC of ethanol–diesel blended fuels increased for the reason that the low heat value of ethanol is about 2/3 of that of the diesel. The increase was especially remarkably at low load conditions. However, the BTE of the engine fueled with ethanol–diesel blend fuel improved with an increase of ethanol content in blend fuels. For example, the BTE increased by up to 1–2% when the engine used the E15–D blend at overall engine operating conditions.
2. The engine smoke opacity can be decreased remarkably over all engine conditions using E15–D and E20–D. Smoke number increased slightly at low load at 2200 rpm when the engine is fueled with E5–D and E10–D.
3. The results of 8-mode tests for E10–D, E15–D, and diesel show that: CO emission decreased by 16.7 and 5.8% for E10–D and E15–D, respectively; NO_x reduced by 2.2 and 4.2% for E10–D and E15–D, respectively; THC increased by up to 40% compared to diesel.
4. CO emissions increased at low and medium loads, but decreased at large and full loads when the engine is fueled with ethanol–diesel blend fuel. On the contrary, NO_x emission decreased at low and medium loads, but increased at large and full loads when the engine is fueled with ethanol–diesel blend fuel. THC increased at various loads at different speed for ethanol–diesel blend fuel.

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