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COMBUSTION VISUALIZATION AND EMISSIONS OF A DIRECT INJECTION COMPRESSION IGNITION ENGINE FUELED WITH BIO-DIESOHOL

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ABSTRACT–The purpose of this paper is to experimentally investigate the engine pollutant emissions and combustion characteristics of diesel engine fueled with ethanol-diesel blended fuel (bio-diesohol). The experiments were performed on a single-cylinder DI diesel engine. Two blend fuels were consisted of 15% ethanol, 83.5% diesel and 1.5% solublizer (by volume) were evaluated : one without cetane improver (E15-D) and one with a cetane improver (E15-D+CN improver). The engine performance parameters and emissions including fuel consumption, exhaust temperature, lubricating oil temperature, Bosch smoke number, CO, NOx, and THC were measured, and compared to the baseline diesel fuel. In order to gain insight into the combustion characteristics of bio-diesohol blends, the engine combustion processes for blended fuels and diesel fuel were observed using an Engine Video System (AVL 513). The results showed that the brake specific fuel consumption (BSFC) increased at overall engine operating conditions, but it is worth noting that the brake thermal efficiency (BTE) increased by up to 1–2.3% with two blends when compared to diesel fuel. It is found that the engine fueled with ethanol-diesel blend fuels has higher emissions of THC, lower emissions of CO, NOx, and smoke. And the results also indicated that the cetane improver has positive effects on CO and NOx emissions, but negative effect on THC emission. Based on engine combustion visualization, it is found that ignition delay increased, combustion duration and the luminosity of flame decreased for the diesohol blends. The combustion is improved when the CN improver was added to the blend fuel.

KEY WORDS : Ethanol-diesel blended fuel, Bio-diesohol, Emission, Combustion image, Diesel engine

1. INTRODUCTION

The degradation of the environment worldwide and foreseeable future depletion of worldwide petrol reserves provide strong encouragement to search for alternative fuels that are friendly to environment but can be used forever. Ethanol is one of the ideal fuels for both diesel and gasoline replacement in CI or SI engines, it had been used to fuel engines since the birth of automotive industry. Ford said, "The fuel of the future is going to from apples, weeds, sawdust-almost everything" (Schuetzle *et al.*, 2002). Since the gasoline is cheaper than ethanol, ethanol dropped out from the engine fuels at that time.

The global crisis in the 1970's triggered the need to develop alternative fuels in order to defend against the vulnerability to oil shortages. In the mid-1970s, considerable attention has been focused on the ethanol fuels. The main advantages of ethanol as engine fuels are: 1) Ethanol is a renewable energy, it can be made from all kinds of raw materials such as sugar cane, molasses, cassava, waste biomass materials, sorghum, corn, barley, sugar beets etc, using already improved and demonstrated technologies. As a result, local agriculture industries can be supported and farmer incomes can be enhanced. 2) Better energy security for many developing countries. The use of ethanol reduces the dependence on crude oil, reducing deficits by replacing oil input from fuels produced from indigenous resources.

These days, ethanol is being used in gasoline engines worldwide. The gasohol improved the octane rate and engine thermal efficiency, and reduced the exhaust emissions dramatically (Poulopoulos *et al.*, 2001; Leonga *et al.*, 2002). In the 1980's, some research efforts have gone into the investigation of ethanol used in diesel engine (Likos *et al.*, 1982; Lu *et al.*, 1996). The main obstacles of ethanol used in C. I. Engines are listed as follows:

(1) Ethanol has limited solubility in diesel fuel. Phase separation and water tolerance with ethanol/diesel blends is a crucial problem.

(2) Ethanol fuel has an extremely low cetane number, so that it can't be used in C.I. Engines directly.

(3) The kinetic viscosity of ethanol is much lower than

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that of the diesel fuel, so that the lubricity is a potential concern with diesohol fuel.

There are several techniques involving ethanol-diesel dual fuel operation: 1) Neat ethanol fuels were used in C. I. Engine by using a Sonex Combustion System (Daly *et al.*, 2001); 2) Dual separated injection system for each fuel, displacing up to 90% of diesel fuel demand; 3) The addition of ethanol to the intake air charge by means of the carburetor or a control valve; 4) Ethanol-diesel blended fuels mixed two fuels prior to injection.

In recently years, with the development of technology, a number of researches have investigated the ethanol-diesel blended fuels used in C.I. Engines (Zhang *et al.*, 2002; Rae, 2002). Especially, AAE Technology Corporation (Irshad Ahamed, 2002), Pure Energy Corporation (Urban Lofvenberg, 2002), and Akzo Nobel Surface Chemistry (Corkwell *et al.*, 2002) developed and produced a low cost additive, which make it possible to blend ethanol with diesel to get a stable and clear fuel. Subsequently, the ethanol-diesel blended fuel can be used in diesel engines. But there are few researches on engine emissions and combustion characteristics for ethanol-diesel blended fuel.

On the basis of this background, the purpose of this paper is to evaluate the effects of ethanol-diesel blended fuel and the cetane improver on engine emissions, performance parameters, and combustion characteristics. Toward this end, an experimental study was performed on a single-cylinder DI diesel engine fueled with 15% ethanol-diesel blended fuel with and without CN improver and neat diesel fuel.

2. FUEL BLENDING PROCEDURE

Usually, the blending of ethanol and diesel fuel was limited to essentially anhydrous ethanol because ethanol is not soluble or has very limited solubility in the diesel fuel (Schuetzle *et al.*, 2002). The solubility of ethanol/diesel mixture is dependent on the hydrocarbon composition of the diesel fuel, wax content and ambient temperature. This solubility is also dependent on the water content of the blend fuels. Phase separation is a crucial issue for ethanol-diesel blends, so that the solublizer is indispensable in blended fuel.

In this test, the commercial diesel fuel and anhydrous ethanol (99.7% purity) were used. The main physical and chemical properties of diesel fuel and anhydrous ethanol are shown in Table 1. Two ethanol-diesel blended fuels were obtained by means of solublizer using the following procedure. The blending protocol was to first blends the solublizer into ethanol, and then blends this mixture into the diesel fuel. The first blends contained only the basic solublizer and the second contained the solublizer and CN improver. Both blended fuels contain 15% ethanol, 83.5% diesel and 1.5% solublizer (by volume).

Table 1. physical and chemical properties of diesel and anhydrous ethanol.

	Diesel	Ethanol
Mole weight	190~220	46.07
Density (@20°C) × 10^3 kg/m^3	0.84	0.789
Boiling point (°C)	180~360	78
Flash point (°C)	78	13.5
Viscosity (cP)	3.35	1.20
Lower heating value (MJ/kg)	42.5	26.8
Auto-ignition temp. (°C)	250	434
Cetane number	45~50	5~8

Table 2. Specifications for the test engine.

Bore × Stroke	100 (mm)×115(mm)
Compression ratio	17.5
Displacement	0.9 (liter)
Injector open pressure	18.1MPa
Advanced angle of injector open	20 °CA BTDC
Nozzle number×Orifice diameter	4×0.32 (mm)
Rated power (kW)	12.1 kW/2200 rpm
Max. torque	58.9 N.m/1760 rpm

3. EXPERIMENTAL APPARATUS

A single-cylinder direct injection diesel engine was employed in this study, the engine specifications are shown in Table 2. Bench tests were performed to measure the performance parameters (torque, fuel consumption, exhaust temperature, lubricating oil temperature) and engine emissions (smoke number, CO, NOx, THC) for ethanol-diesel blended fuels and diesel fuel.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The engine performance and emissions at various loads under different engine speeds (2200 rpm and 1760 rpm) using ethanol-diesel blended fuels and diesel fuel was investigated, and parameters including torque, power, fuel consumption, exhaust temperature, oil temperature, smoke number, Carbon monoxide (CO), Oxides of Nitrogen (NOx), and total hydrocarbon (THC) were measured.

4.1. Brake Specific Fuel Consumption

Based on the experimental results, the Brake specific fuel consumption (BSFC) of the test engine fueled with blended fuels and diesel fuel were calculated. The

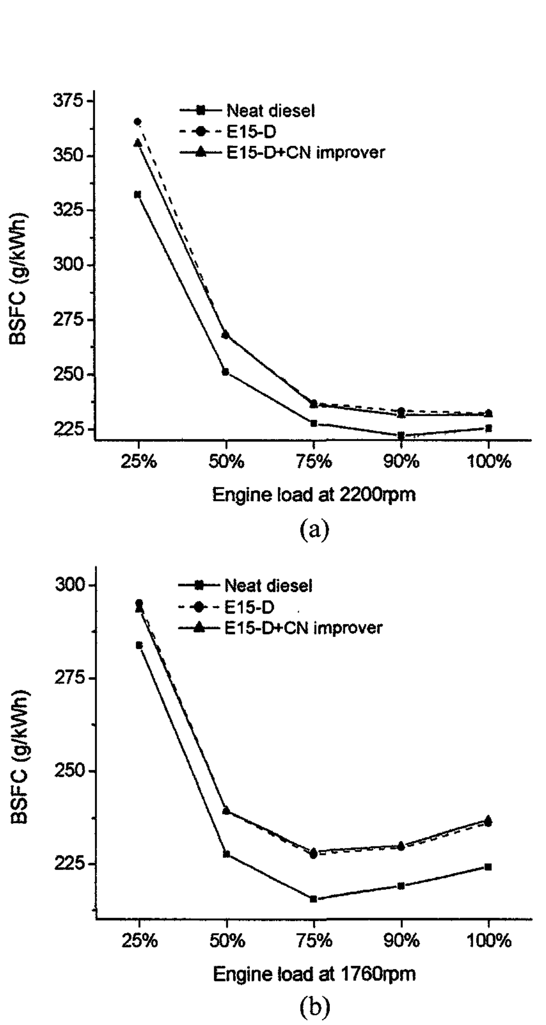


Figure 1. Brake specific fuel consumption versus engine load for ethanol-diesel blend fuels and neat diesel.

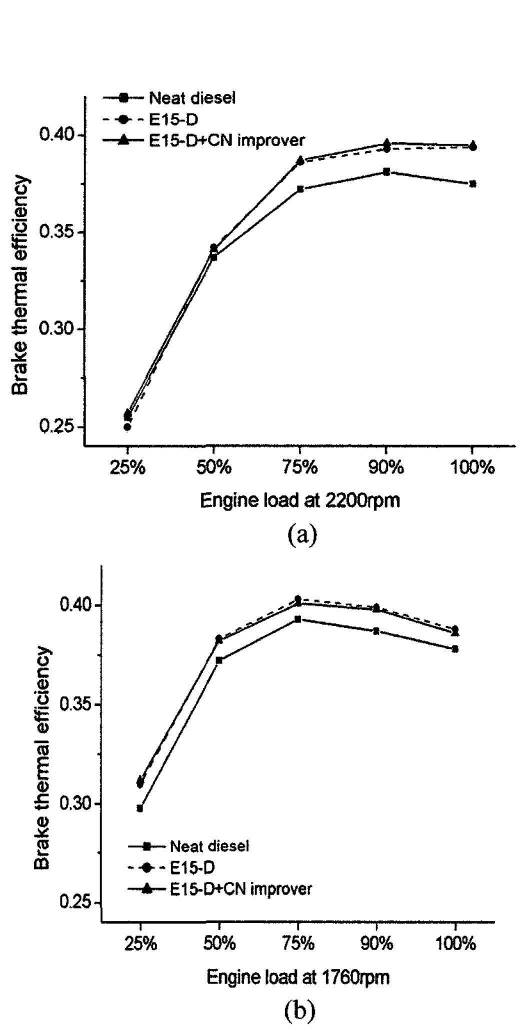


Figure 2. Brake thermal efficiency versus engine load for diesohol and neat diesel.

relationship between BSFC and various loads at 2200 rpm and 1760 rpm with different fuels is presented in Figure 1. The BSFC decreased with an increase in engine load, but a slightly increased after 75% load at 1760 rpm. It is evident that the BSFC of ethanol-diesel blended fuels are higher than that of the diesel fuel. This is due to the fact that the lower heating value of ethanol is lower than that of the diesel fuel. Moreover, it is found that there is no distinct effect of the cetane number improver on BSFC.

4.2. Brake Thermal Efficiency

The engine brake thermal efficiency was further calculated from BSFC and low heat value of the blended fuel. The calculated results are shown in Figure 2. It is indicated that the brake thermal efficiency (BTE) improved at medium and large loads at two engine test speeds. In particular, the BTE increased from 37.2% to 39.5% at full load under 2200 rpm in the case of ethanol-diesel blended fuels. The BTE improved about 1.2% (absolutely) at medium and large loads under 1760 rpm. There is no distinct effect of the cetane number enhancer on BTE.

The results shows that the engine brake thermal efficiency can be enhanced remarkably by means of adding ethanol to diesel fuel. This can be explained by the following reasons: the combustion is more complete in the fuel-rich zone for the oxygen of ethanol, so that the combustion efficiency is enhanced; the quality of spray with blend fuels may be improved for the reason that the boiling point of ethanol is lower than that of the diesel.

4.3. Smoke Emission

The Bosch smoke number was measured for all three fuels with the engine at various loads under 2200 rpm and 1760 rpm. For the 15% ethanol-diesel blended fuel without CN improver, an average reduction of above 50% of smoke number at all loads under 2200 rpm. It is surprising that the smoke number with 15% blend fuel + CN improver at 2200 rpm increased compared to the

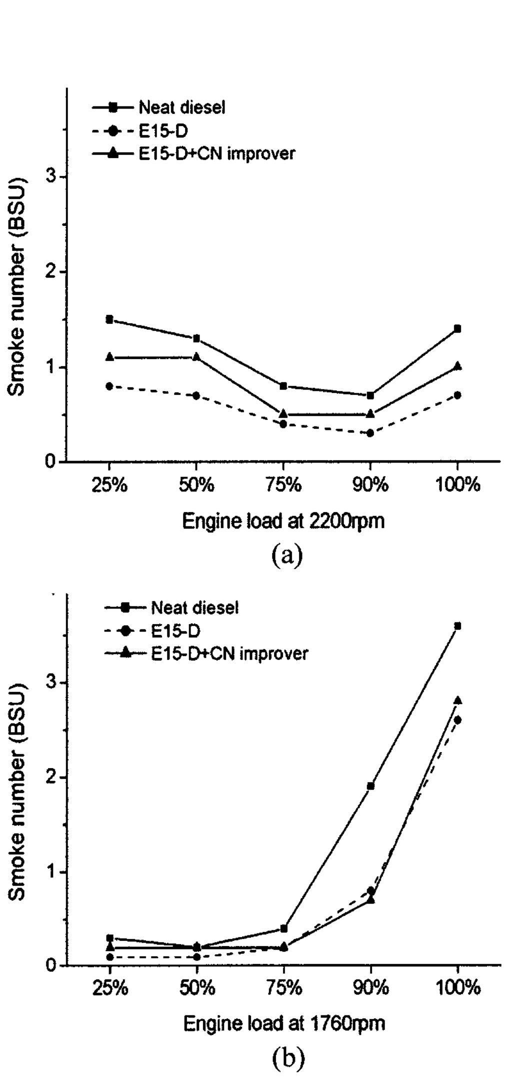


Figure 3. The relationship between smoke and ethanol contents in blend fuels and neat diesel.

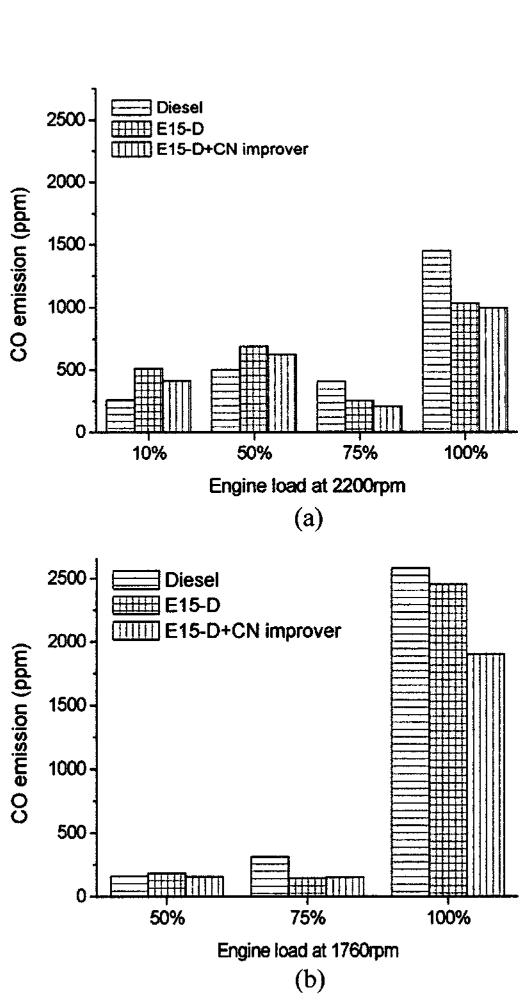


Figure 4. CO emissions versus engine load with ethanol-diesel blend fuels and neat diesel.

blended fuel without CN improver, but it is still lower than that of diesel fuel. The smoke number decreased remarkably at relatively large load under 1760 rpm for blended fuels.

4.4. Gas Pollutant Emissions

The emissions of THC, CO, and NOx were further measured. The AVL CEB Gas Analyzer was used as measuring device.

CO emissions at various loads under different engine speeds are presented in Figure 4. At rated speed, CO increased by up to 95.5% and 36.7% at 10% load and 50% load with ethanol-diesel blended fuel, increased 58.7% and 24% at the same load for the ethanol-diesel blended fuel with CN improver when compared to diesel fuel. At high load under rated speed, CO decreased significantly with an increase of load for both ethanol-diesel blended fuels. Moreover, at high engine load, CO emissions decreased slightly more for the blended fuel with CN improver than for the blended fuel without the CN improver.

At 1760 rpm, CO emissions at full load are very high. For both ethanol-diesel blend fuels, CO emissions decreased at 75% load and full load, and CO emissions of blend fuel with CN improver are lower than that of the blended fuel without CN improver.

Based on the analysis, the general characteristics of CO emissions for ethanol-diesel blended fuels can be obtained: CO emissions increased at low and medium loads, but reduced at large and full loads compared to the diesel fuel; for blended fuel with CN improver, CO emissions are lower than that of the blended fuel without CN improver at overall engine operating conditions. So that, the ethanol-diesel blended fuel with CN enhancer is effective in reducing the CO emissions.

The NOx emissions of the engine using different blended fuels and diesel fuel under various operating conditions are shown in Figure 5. It can be seen obviously that the general tendency of engine NOx

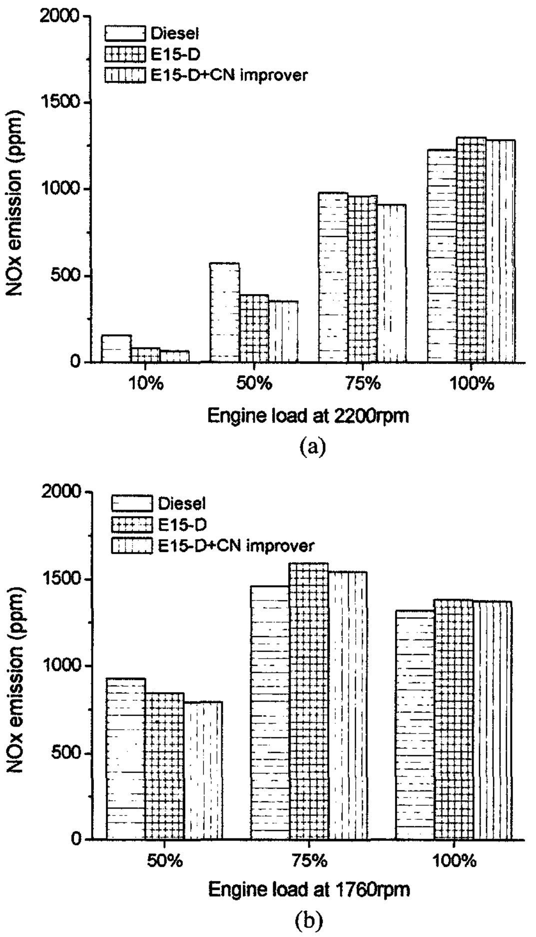


Figure 5. NOx emissions versus engine load with ethanol-diesel blend fuels and neat diesel.

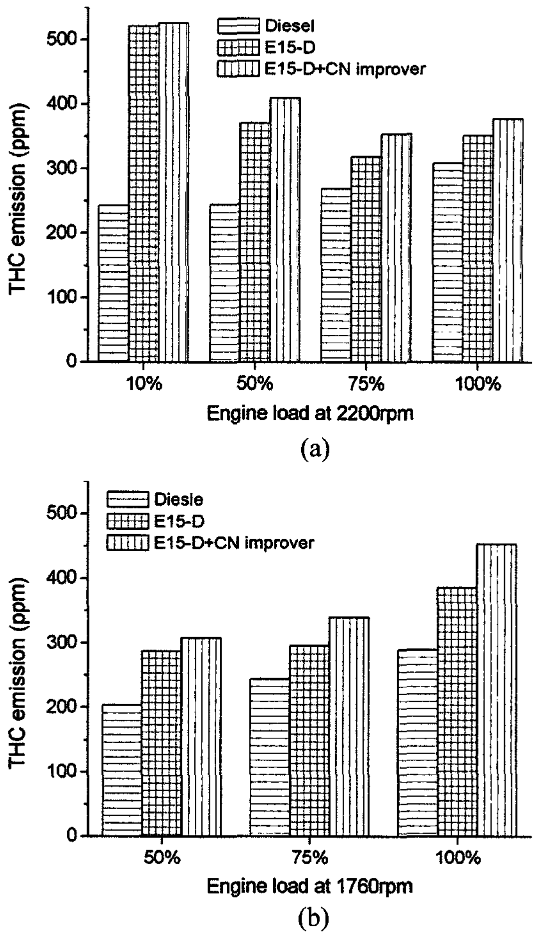


Figure 6. THC emissions versus engine load with ethanol-diesel blend fuels and neat diesel.

emissions is opposite to the CO emissions. For an engine speed of 2200 rpm, both ethanol-diesel blended fuels reduced the NOx about 50%–60% and 32–35% at low load and medium load, respectively, but reduced a small level at 75% load. At full load, NOx is slightly higher for blended fuels than diesel fuel. The similar tendency can be seen for an engine speed of 1760 rpm. Furthermore, NOx emissions for blended fuel with CN improver are lower than that of blend fuel without CN improver at overall engine operating conditions.

Figure 6 shows the effect of ethanol on THC production. It can be found that with the introduction of ethanol in diesel, the THC emissions increased at various engine conditions. For blended fuel with CN improver, the THC levels are higher than blended fuel without the CN improver. The increase of the THC levels is a result of incomplete combustion of the blended fuel at low load and medium load.

Comparing the CO emissions and NOx emissions for blended fuels at various operating conditions from Figure 4 and Figure 5, it is of interest to note that the NOx emissions decreased with the increase of CO emissions at low and medium loads, but NOx slightly increased with the decrease of CO at large and full loads. One explanation, which has been offered for this trade-off between CO and NOx emissions is that, low combustion temperature results from lean fuel-air mixture and increased combustion duration at low and medium loads, but high combustion temperature results from rich fuel-air mixture and decreased combustion duration at large and full loads. Another interesting phenomenon can be found is that the cetane improver has positive effect on CO and NOx emissions, but negative effect on THC emissions.

5. COMBUSTION IMAGES AND ANALYSIS

In order to understand the effects of ethanol on engine performance and emissions, combustion behavior was observed by means of direct photography. There is no modification of engine parameter except for a new cylinder head, which allow the optical access to the combustion chamber by using an endoscope-based measurement system. The measurement system is AVL EVS 513. The flame images for blended fuels and diesel fuel under the same operating condition are shown in Figure 7. The combustion characteristics of blended fuels can be seen from the engine combustion processes fueled with neat diesel, E15-D, and E15-D+CN improver as follows:

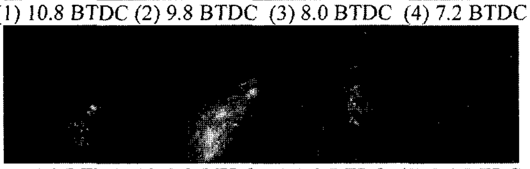
Ignition delay. The most apparent change of the combustion behavior when burning ethanol-diesel blended fuels is an increase in the ignition delay time. At 12.2 0CA Before Top Dead Center (BTDC), the flame has developed overall combustion chamber for neat diesel,

(1)12.2 BTDC (2) 9.8 BTDC (3) 8.0 BTDC (4) 7.2 BTDC

(5) 5.0 BTDC (6) 3.8 BTDC (7) 2.0 BTDC (8) 0.8 BTDC

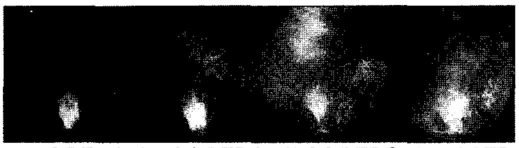
(a) Diesel

(1) 10.8 BTDC (2) 9.8 BTDC (3) 8.0 BTDC (4) 7.2 BTDC

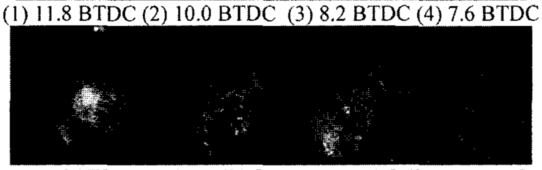


(5) 5.0 BTDC (6) 3.8 BTDC (7) 2.0 BTDC (8) 0.4 BTDC

(b) E15-D



(1) 11.8 BTDC (2) 10.0 BTDC (3) 8.2 BTDC (4) 7.6 BTDC



(5) 5.2BTDC (6) 3.4 BTDC (7) 2.2 BTDC (8) 0.4 BTDC

(c) E15-D+CN improver

Figure 7. Flame images during the combustion process for ethanol-diesel blended fuels and neat diesel.

but there is no flame occurred until 9.8 0CA BTDC for E15-D and 11.8 0CA BTDC for E15-D+CN improver, respectively.

Combustion duration. From the figure, it can be found that the combustion duration for both ethanol-diesel blended fuels decreased evidently. The flame can be seen during 9.8 0CA BTDC~3.8 0CA BTDC for E15-D and 11.8 0CA BTDC~2.2 0CA BTDC for E15-D+CN improver, respectively. One explanation for the decreased combustion duration is that, enhanced local air-fuel ratio for the oxygen of ethanol, which improved fuel combustion. The other reason is that, enhanced mixing results from the "micro-explosion" of the blended fuels.

Luminosity. Combustion images revealed that the luminosity of flame decreased with the ethanol-diesel blended fuels, relative to diesel fuel. This means that the soot emission decreased when engine fueled with ethanol-diesel blended fuels.

6. CONCLUSIONS

This work was undertaken to study and compare the effects of 15% ethanol-diesel blended fuels and cetane number improver on brake specific fuel consumption, brake thermal efficiency, exhaust emissions (smoke number, CO, NOx, and THC), and combustion characteristics in a single-cylinder diesel engine. The following conclusions can be drawn from this study:

(1) The brake specific fuel consumption of 15% ethanol-diesel blended fuels was increased for the reason that the lower heating value of ethanol is only 2/3 of that of diesel, especially increased remarkably at low load conditions. But the brake thermal efficiency of engine fueled with diesohol increased by up to 1%–2.3% at overall engine operating conditions. There is no distinct effect of CN improver on engine fuel consumption.

(2) Engine smoke emission decreased remarkably at overall engine operating conditions using ethanol-diesel blended fuels than that of diesel fuel.

(3) CO emissions increased at low and medium loads, but decreased at large and full loads when the engine was fueled with diesohol. On the contrary, NOx emissions decreased at low and medium loads, but increased at large and full loads when the engine was fueled with diesohol. THC increased at various loads under different engine speeds for diesohol.

(4) Typical characteristics of ethanol-diesel blended fuelsignition delay increased, combustion duration and luminous flame decreased were observed using Engine Video System. However, it is find that the ignition delay decreased, combustion duration and the luminosity of flame increased when the cetane improver was added to the blended fuel.

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