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FUEL PROPERTIES AND EMISSIONS CHARACTERISTICS OF ETHANOL-DIESEL BLEND ON SMALL DIESEL ENGINE

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ABSTRACT–Phase separation and low cetane number are the main barriers to the large-scale use of ethanol-diesel blend fuel on small diesel engines. In this paper, an additive package is designed on the basis of the blended fuel properties to overcome these limitations. The experiments show that the solubility of ethanol in diesel is evidently increased by adding 1~2% (in volume) of the additive package and the flammability of ethanol-diesel blend fuel with the additive has reached the neat diesel level under the cold start conditions. Effects of the ethanol content in diesel on fuel economy, combustion characteristics, and emission characteristics are also investigated with the ethanol blend ratios of 10%, 20% and 30%. The increase in ethanol content shows that the specific fuel consumption and the brake thermal efficiency are both gradually increased compared to neat diesel. The soot concentrations of the three blended fuels are all greatly lower than that of neat diesel. NO_x emission is increased with an increase in the engine load and is reduced with the increase in the ethanol blend ratio under a high load.

KEY WORDS : Ethanol-diesel blend, Cosolvent, Cetane improver, Combustion, Emission

1. INTRODUCTION

The increasing number of motor vehicles aggravates a shortage of petroleum supply in China. It is reported that the crude oil consumption in China in 2005 went up to 317 million tons and 42.9% of that amount, 136 million tons, was imported (Zhu, 2006; Li, 2006; Liu, 2006; Yu, 2006). China continues to be the world's third largest crude oil importer after the United States and Japan. The huge consumption of fossil fuels brings a severe issue of air pollution. Therefore, developing alternative and cleaner automotive fuels becomes urgent issues. Ethanol, one of the renewable energy sources, has been extensively introduced into the market in the form of ethanol-gasoline blended fuel in nine provinces of China till now (National Development and Reform Commission of PRC, 2004). In the nine provinces, the sale of gasoline fuel is permitted only if it is blended with ethanol (10% ethanol and 90% gasoline). The corresponding national standards on ethanol-gasoline blended fuel (denoted E-gasoline) were set in 2004 (Standardization Administration of China, 2004). As with gasoline, the retail price of diesel is still rising and has risen to nearly as high as that of gasoline (Liu, 2005). In addition, more and more agricultural machines equipped with diesel engines are being used in the vast countryside of China. These drive the Chinese government to pay more attention to the ethanol-diesel blend fuel (denoted E-diesel). However, E-diesel's low cetane number and its phase separation at low temperatures have limited the use of the blended fuel (Corkwell *et al.*, 2002). Wang *et al.* (2002) and He *et al.* (2003) reported the effect of E-diesel on engine's power performance, fuel economy, and emission characteristics. Lü *et al.* (2004, 2005) investigated the variation of fuel properties and cetane number of the E-diesel with the ethanol blend ratio increasing. The study that used gasoline as a cosolvent between diesel and ethanol had also been conducted (Xu *et al.*, 2003). However, the researches on an additive package, especially on low molecular ether, which can both improve the E-diesel's mutual solubility and cetane number, are still few. In order to overcome the limitations of E-diesel on small diesel engines, an additive package that consists of medium alcohol, low molecular ether, macromolecule polymer and alkyl nitrate is designed. Adding this additive package within a range of 1%~2% (in volume) can evidently improve the mutual solubility of E-diesel.

Engine bench tests under various ethanol blend ratios indicate that the cold starting performance of E-diesel is better than that of neat diesel; with an increase in the

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Table 1. The physical and chemical properties of diesel and five alcohols.

	Methanol	Ethanol	Propanol	Butanol	Pentanol	Diesel $(-10^{\#})^{*}$
Molecular formula	CH_3OH	C_2H_5OH	C_3H_7OH	C_4H_9OH	$C_5H_{11}OH$	C_{12}~C_{22}
Molecular weight	32	46	60	74	88	180~220
Oxygen content (%)	50	34.8	26.7	21.6	18.2	0.4~0
Specific weight	0.791	0.787	0.804	0.81	0.817	0.81~0.84
Boiling point (°C)	64.7	78.3	97.2	117.7	138	185~340
Freezing point (°C)	−97.8	−114	−126	−90	−79	−10 ~ −14
Flashing point (°C)	11	13	15	28	33	65
Autoignition temperature (°C)	465	426	430	441	327	270~350
Ignition limit (vol%)	6.7~36	4.3~19	2.6~13.5	1.45~11.25	1.2~10.5	1.5~8.2
Cetane number	3	8	12	17	20	40~45
Low heat value (MJ/kg)	20.1	27.1	30.9	33.4	35.1	43.8
Mixture heat value (MJ/kg)	2.708	2.708	2.713	2.73	2.738	2.73
Reid vapor pressure (mmHg)	232.4	130	48	19	8	69
Gasification latent heat (MJ/kg)	1.1	0.86	0.69	0.594	0.427	0.25~0.27
Solubility (g/100gH_2O)				8	2.3	~0

$^{*}-10^{\#}$ indicates that the freezing point of the diesel is −10°C

blend ratio, the specific fuel consumption is increased, while the Bosch smoke number is decreased. The variations of emissions of THC, CO and NO_x under various engine loads are also investigated.

2. E-DIESEL FUEL PROPERTIES AND ADDITIVE PACKAGE

The physical and chemical properties of light diesel and five alcohols are listed in Table 1. According to the data, it is obvious that with the increase in carbon atomic number, the fuel properties of alcohols gradually reach that of diesel level. As to ethanol, it has noteworthy characteristics in three aspects.

(1) Oxygen weights make up 35% of the mass of the ethanol. The low heat value of ethanol is equivalent to only 62% that of diesel, but its mixture heat value is very close to that of diesel.
(2) Its flammability limit is broader than that of diesel at the lean side, which is a great advantage to the stability of lean burn and to reducing emissions.
(3) Its cetane number is much lower than that of diesel, but the gasification latent heat is much higher than for diesel.

Directly blending ethanol with diesel, as with E-gasoline, is a convenient way to use E-diesel, but if even a slight amount of water is blended, it will bring about phase separation due to the hydrogen bond produced by the hydroxyl of ethanol combining with water molecules. Another problem is the low cetane number of the blended fuel, which will reduce rapidly with an increase in the ethanol blend ratio. In addition, there are other problems, including the high gasification latent heat of ethanol. All these problems make the cold starting performance and emission performance of the E-diesel different from that of neat diesel. Therefore, only by overcoming these problems can the use of E-diesel becomes feasible and widespread.

2.1. Mutual Solubility

The solubility of ethanol in diesel (in addition to the water content in the ethanol and the aromatic hydrocarbon content in the diesel fuel) is related to the ethanol blend ratio and to the temperature of the solution. Figure 1 shows the binary phase diagram of $-10^{\#}$ diesel and ethanol, in which the area above the curve is the single-phase area and the area below is the two-phase area.

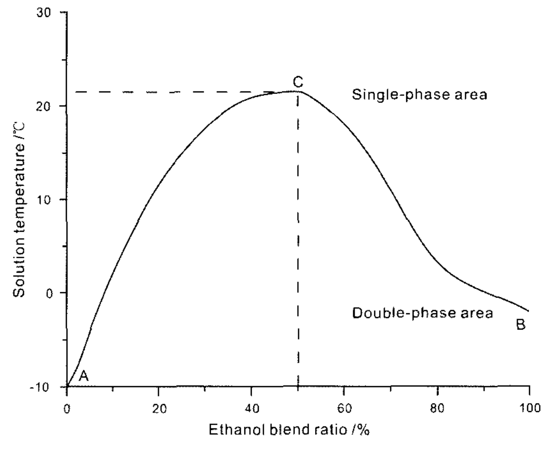


Figure 1. The binary phase diagram of diesel and ethanol.

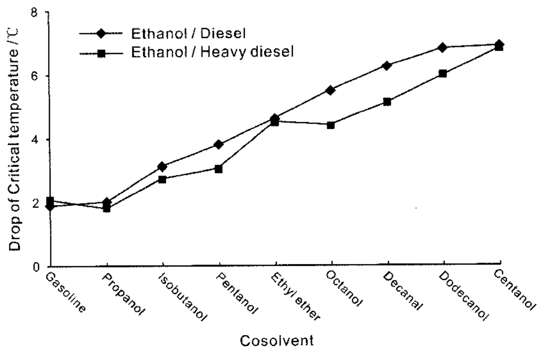


Figure 2. Effects of the cosolvents.

Curve AC represents the variation of ethanol concentration in the diesel phase depending on the solution temperature, and curve BC represents the variation of diesel concentration in the ethanol phase. The two curves intersect at C, called the critical point, where the temperature is 21.8°C and the ethanol blend ratio is about 50%.

The water tolerance in E-diesel is so small that E-diesel consisting of 10% ethanol and 90% diesel cannot be used during most of the year, even with stringent control of the water content and the temperature differences between day and night during transportation and storage (US. DOE, 1978). Therefore, it is necessary to find a cosolvent to promote the solubility of ethanol in diesel at lower temperatures. Figure 2 shows the cosolvent effect of some chemicals (Murayama, 1982). The horizontal axis indicates the types of cosolvent, and the vertical axis indicates the drop values of critical temperature after blending 1% cosolvent (in volume). It is obvious that the more this value drops, the greater the cosolvent effect. As shown, several medium carbon alcohols, high carbon alcohols and ethyl ether are suitable as cosolvents, while gasoline is not suitable due to its poor cosolvent effect and its low cetane number of 12 (Xu, 1983).

Moreover, in evaluating a cosolvent, its production costs and the universality of its production materials must also be taken into account. Therefore, it is appropriate in this study to use a mixture of isobutyl alcohol, amyl alcohol and low ether as the cosolvent.

2.2. Flammability

The cetane number of ethanol is only 8. Adding 10%~15% ethanol into the diesel fuel will make the cetane number of the blend fuel drop 6~9 (Corkwell *et al.*, 2002), which will extend the ignition delay period, increase the rate of pressure rise and make cold starting difficult. Therefore, it is necessary to add a cetane improver into the E-diesel, to improve the flammability of the blended fuel.

The cetane improvers now commonly used for diesel fuels are alkyl nitrates and organic peroxides (Dong *et al.*, 1996). Ethers are also high-quality cetane improvers (Ogawa *et al.*, 2002). The cetane number of ethyl ether is 126, and this value for butyl ether is 100.

Alkyl nitrates are more easily decomposable than diesel. When they decompose at lower activation energy levels, it will produce alkoxy radicals (R•), which can sequentially decompose into new free radicals and aldehydes during the ignition delay period. This process will accelerate the preflame reaction of diesel and shorten the ignition delay period.

According to Thompson (Thompson, 1997), the improved cetane number after adding the alkyl nitrates and organic peroxides into the diesel fuel can be evaluated by the empirical formula below.

$$CNI=A\times CN^{0.36}\times G^{0.57}\times C^{0.032}\times \ln(1+17.5\times C) \qquad (1)$$

CNI represents the improved cetane number, CN is the original cetane number of the diesel, and A is the component constant. For alkyl nitrates, A=0.16; for organic peroxides, A=0.119 (Thompson, 1997), and G is the API gravity of diesel. G=40~50 (Thompson, 1997), and C is the volume fraction of the added materials.

Generally, the cetane number of $-10^{\#}$ diesel is 40~45. If 0.3% (in volume) alkyl nitrates is added to E-diesel composed of 10% ethanol and 90% diesel, and to E-diesel composed of 15% ethanol and 85% diesel, the corresponding CNI values are 9.21 and 8.95, respectively. Thus, it can be derived that, for E-diesel in which the ethanol blend ratio is less than 15%, the cetane number can reach the neat diesel level after mixing a very small quantity of alkyl nitrates.

2.3. Additive Package

An excellent additive must have a high cosolvent effect, good flammability and in addition a certain viscosity, to maintain the lubricity of the fuel. Besides, the combustion product must not contain residues, which would be likely to block injector orifice holes.

In this study, titration experiments were performed to investigate the cosolvent effect of alcohols and ethers. The results show that the more similar the nonpolar group of one chemical is to that of diesel, the better the ethanol or ether will disperse in diesel and the less of this cosolvent will be needed.

The medium and high carbon alcohols have low cetane numbers and poor flammability. The low ethers have significant effects on the instability of E-diesel because they are too volatile (although they can promote combustion). Thus, a mixture of an isomer of a medium carbon alcohol and a low ether is chosen as the cosolvent in the additive package. Furthermore, the product materials are inexpensive and easily available.

As to this new additive package, the carbon atomic

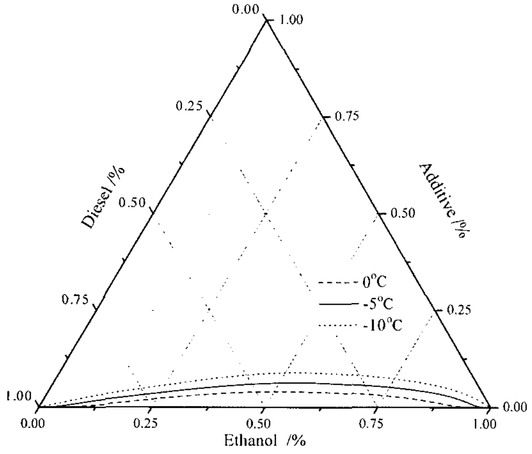


Figure 3. Ternary phase diagram of diesel, ethanol and additive.

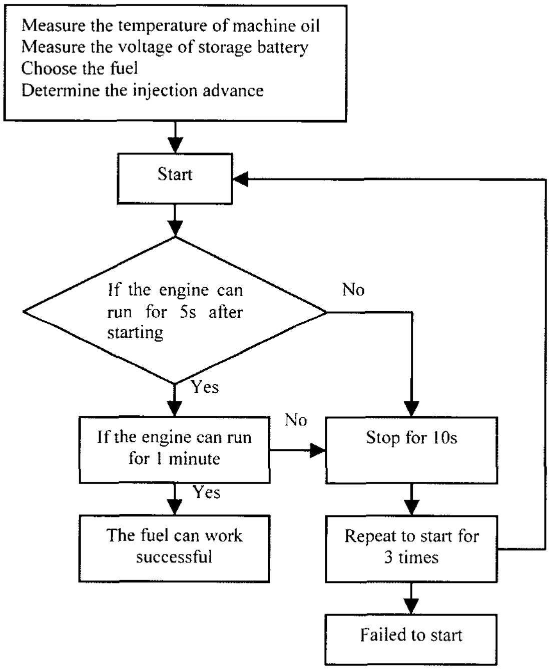


Figure 4. Flowchart of cold starting.

number for the medium alcohol is identical to that of the low ether, so the alcohol molecules will associate with the ether, to restrain the ether molecules from escaping. Moreover, the ratio of alcohol to ether can be easily adjusted to satisfy the required volatility in different seasons.

There are many types of alkyl nitrates and each one has different effect on improving the cetane number (Dong *et al.*, 1996). In this study, isooctyl nitrate has been determined as the best cetane improver, according to engine bench tests.

The additive also contains a high polymer component, for its emulsification, to prevent the phase separation when water is introduced into the mixture. The high polymer also has a high molecular weight and high viscosity, so it can form a viscous film around the separate phases, to improve the lubricity of E-diesel.

Table 2. Engine specifications.

Item	Value
Bore × stroke (mm)	105×115
Displacement (L)	0.966
Compression ratio	17.1
Nominal horsepower (kW)	12.1 kW/2200 rpm
Maximum torque (N·m)	58.8
Injection advance (°CA)	22°CA BTDC
Injection holes	4
Nozzle diameter (mm)	0.32

In summary, the new additive package consists of isobutyl alcohol, low ether, a high polymer and isooctyl nitrate, and the volume fraction ratio of these four components is 1:3:1:1. The ternary phase diagram of diesel, ethanol and the additive package is shown in Figure 3, in which three isotherms at −10°C, 0°C and 5°C, are illustrated, respectively. It can be observed in Figure 3 as follows.

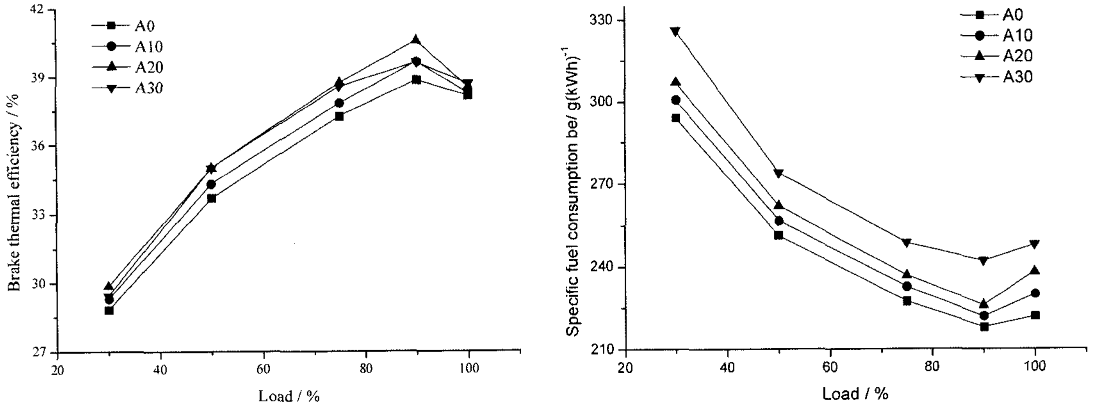
(1) Adding only a little of the additive package can notably improve the solubility of ethanol in diesel. For example, to dissolve 15% ethanol at 0°C only needs 1% of the additive package, and even at −10°C, the required dosage is no more than 2%.

(2) With an increase in fuel temperature, the needed dosage of the additive package is gradually reduced, and the maximum value always appears at the critical point C, which is well in accord with the conclusion of the binary phase diagram.

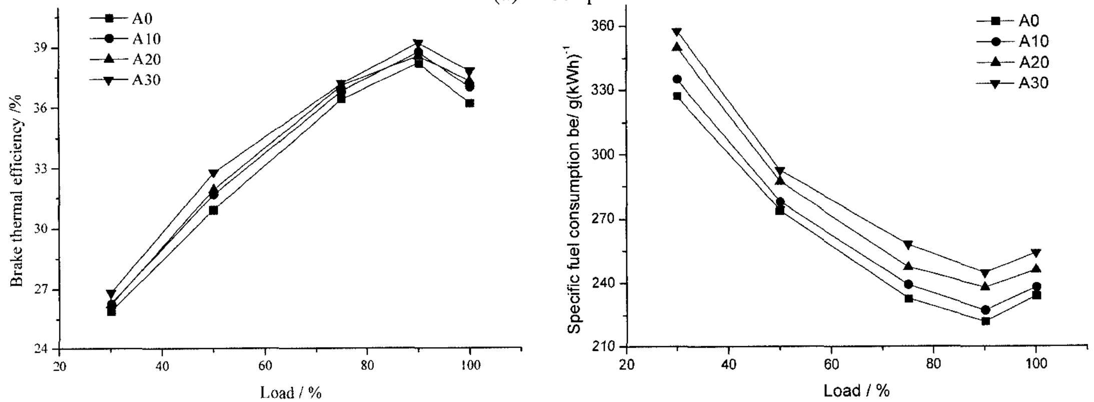
As with E-gasoline, E-diesel is easily blended with 10%~15% ethanol (Murayama, 1982). Taking the E-diesel composed of 13.5% ethanol, 85% diesel and 1.5% of the additive package as an example, there is 0.3% isooctyl nitrate in it. According to Equation (1), plus the contribution of ether to cetane, the cetane number of this E-diesel has been slightly more than that of the neat diesel.

3. BENCH TESTS

To verify the effect of the additive package on cold starting performance and the emissions performance, engine bench tests were implemented using four types of fuel: 1) neat −10# diesel (denoted A0); 2) a blend of 8.5% ethanol, 90% diesel and 1.5% additive package (denoted A10); 3) a blend of 18% ethanol, 80% diesel and 2%



(a) 1200 rpm



(b) 1700 rpm

Figure 5. Effect of E-diesel on brake specific fuel consumption and brake thermal efficiency.

additive package (denoted A20); and 4) a blend of 27.5% ethanol, and 70% diesel and 2.5% additive package (denoted A30). A single cylinder, four-stroke direct injection 1105 diesel engine, whose specifications are listed in Table 2, was employed. The ambient temperature in laboratory ranged from –7°C to –5°C.

3.1. Cold starting Performances

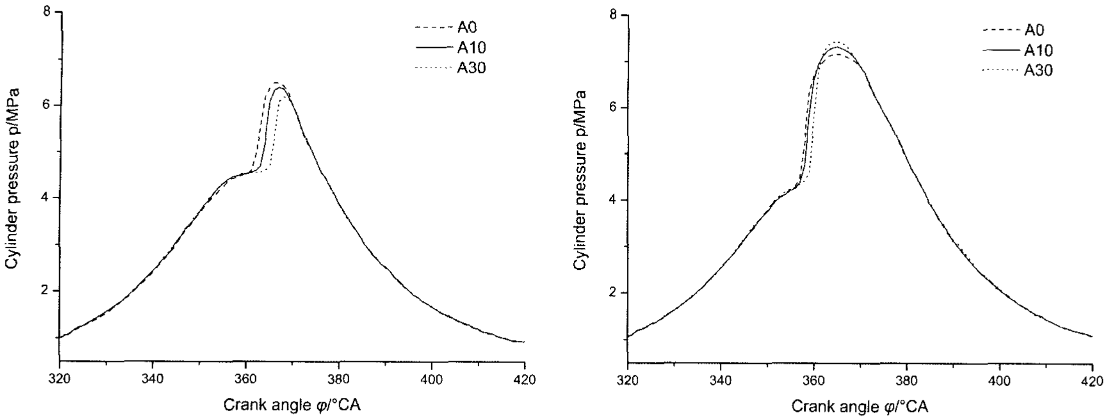
Figure 4 shows the process of cold starting. The bench tests were conducted by first adjusting the injection advance and verifying that the machine oil temperature was below –5°C. Then the engine was started for 10 seconds. If the engine could run for longer than a minute after ignition, the cold starting was considered successful. The experimental results show that when the engine was fuelled with A30, three consecutive attempts at cold starting all failed, but when the engine was fuelled with A0, A10, and A20, all tests were successful with only one start. The A10 and A20 fuels started the engine more easily and smoothly than did the A0. It evidently proved that the low ether and the isooctyl nitrate can promote the flammability of E-diesel. Being limited by the ambient temperature, cold starting experiments were not performed at temperatures below –10°C.

3.2. Fuel Economy

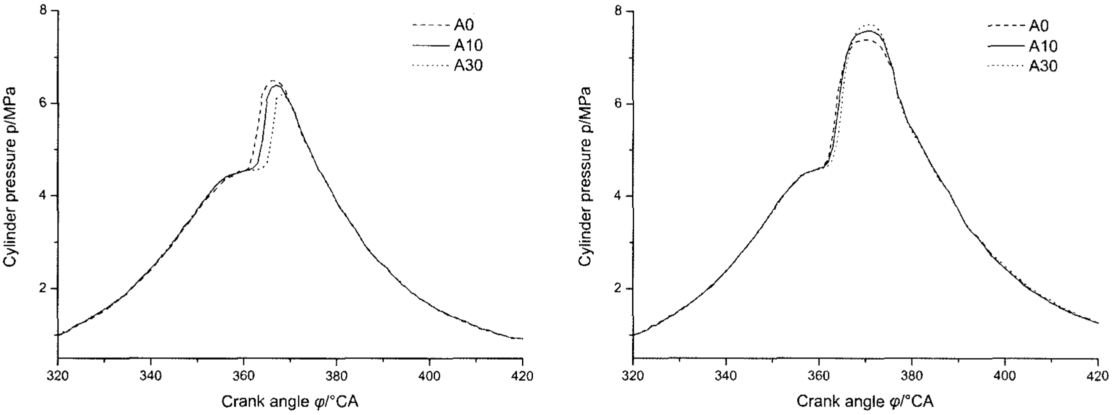
Figure 5 shows the load characteristics of the A0, A10, A20, and A30 fuels, under revolutions of 1,200 rpm and 1,700 rpm. Because the heat value of ethanol is equivalent to only 62% of that of diesel, the specific fuel consumption (in specific weights) of each type of E-diesel is higher than that of neat diesel. The consumption of A10, A20 and A30 are 2.3%, 5.3% and 9.5% higher than that of A0, respectively; but the corresponding brake thermal efficiencies are improved by 0.55%, 0.94% and 1.06%, respectively. It is clear that the combustion of ethanol requires less oxygen than that of diesel. This would have a positive effect on forming the homogeneous mixture of fuel and air in the diffusion combustion stage, especially with an engine under high loads.

3.3. Combustion Characteristics

The variations of in-cylinder pressure that result from changes in crank angle and the ethanol blend ratio are shown in Figure 6. With an increase in ethanol blend ratio, the highest pressure is observed to have an increasing trend under high load, with a 1% and a 2.6% increase for A10 and A30, respectively. Figure 7 shows the heat release rates of the fuels. Further, it is shown in



(a) n=1200 rpm, Pe=2.5kW (b) n=1200 rpm, Pe=8.3kW



(c) n=1700 rpm, Pe=3.5kW (d) n=1700 rpm, Pe=11.4kW

Figure 6. Effect of E-diesel on cylinder pressure.

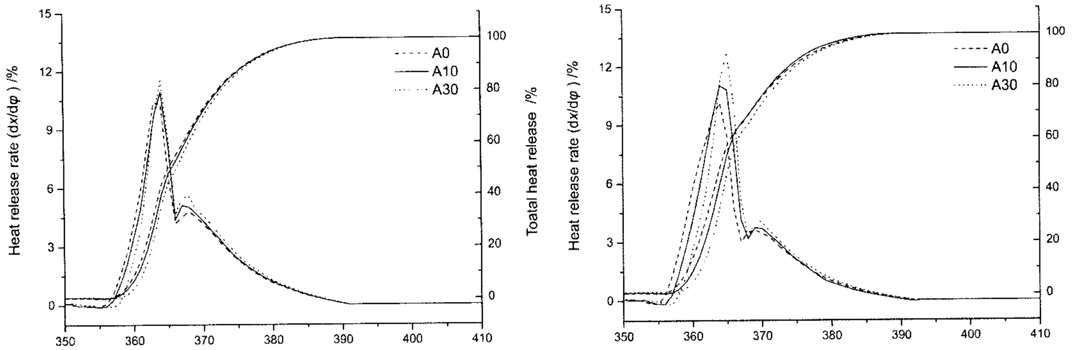
Figure 7 that the ignition delay increases with an increase in the ethanol blend ratio, which is also indicated in Figure 6. Under partial load, A10 and A30 are ignited at 1°CA and 2.5°CA later than ignition for neat diesel, and under high load, the values are 0.5°CA and 1.5°CA, respectively. This is due to the higher gasification latent heat of ethanol, which will lower the temperature inside the cylinder, particularly when the engine is under partial load. Although the ignition delay periods of the blended fuels are prolonged, the combustion durations become even shorter. This indicates that the addition of ethanol has promoted the combustion of diesel fuel and increased the brake thermal efficiency of the engine.

3.4. Soot

Soot is the main component of particulate matters, occupying more than 50% of the particulate mass under high speeds and high loads (Wang *et al.*, 2001). The soot intensities were tested by using an AVL Dismoke 4000 smoke meter. Figure 8 shows the effects of the different E-diesel fuels on soot intensity. It can be observed that for A10, even under high loads, the soot intensity is equivalent to only half the values for A0; and for low loads the ratio is even less. With each increase in the ethanol blend ratio, the smoke intensity becomes less and less. This could be due to the lower viscosity of E-diesel, the high gasification latent heat of ethanol and the high oxygen content in ethanol (relative to diesel). Lower viscosity makes E-diesel atomize better; high gasification latent heat will depress the flame temperature at the preliminary combustion stage to avoid fuel droplets clustering; and high oxygen content will promote oxidation at later combustion stages.

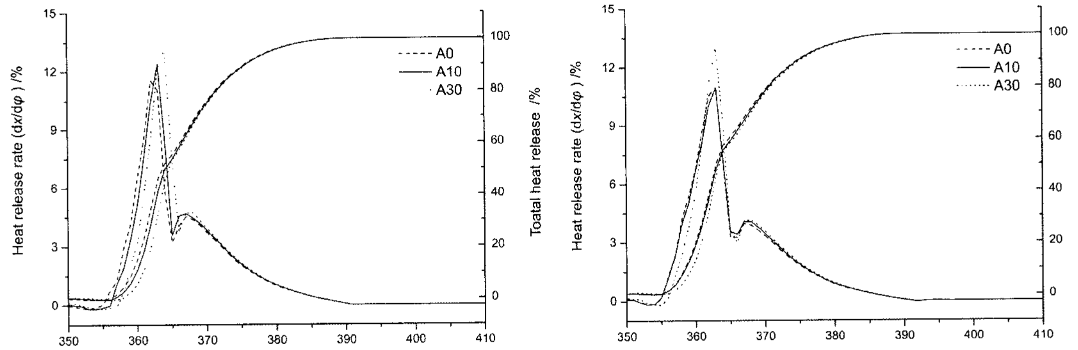
3.5. THC, CO and NO_x Emissions

Figure 9, Figure 10 and Figure 11 show the emission concentrations of THC, CO and NO_x, respectively. The THC emission reduces when the load increases under the two revolutions with the same ethanol blend ratio. This is thought to be because THC emission is relative high under low loads, since the addition of ethanol lowers the flame temperature. In addition, the quench layer near the cylinder wall, caused by a cooling effect due to the evaporation of ethanol, is another reason why THC is



(a) n=1200 rpm, Pe=2.5kW

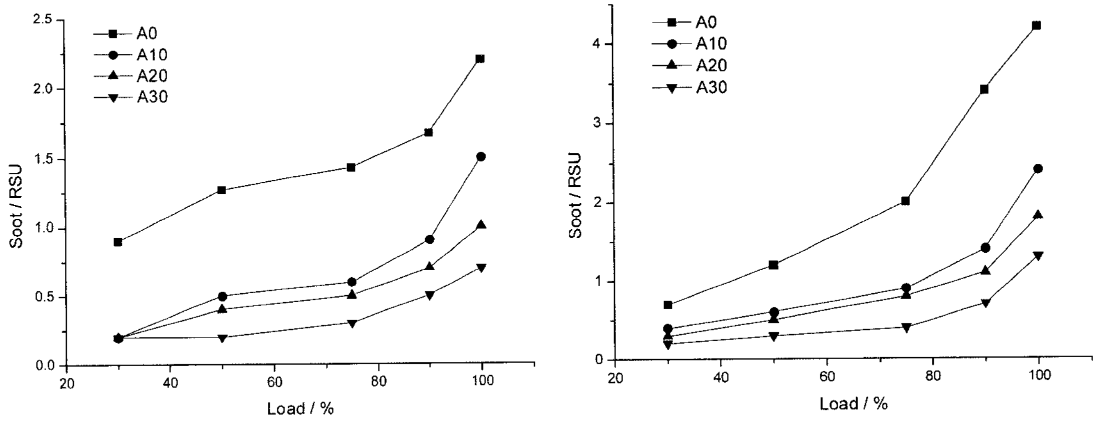
(b) n=1200 rpm, Pe=8.3kW



(c) n=1700 rpm, Pe=3.5kW

(d) n=1700 rpm, Pe=11.4kW

Figure 7. Effect of E-diesel on heat release.

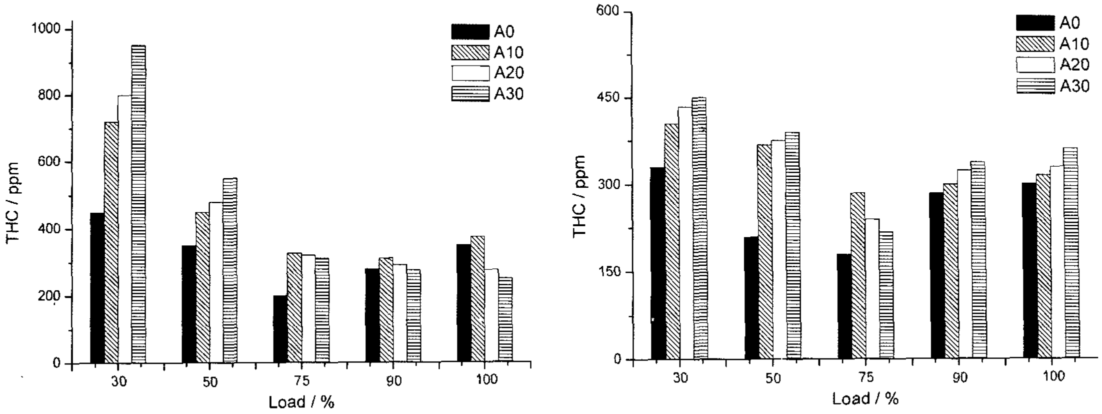


(a) 1200 rpm

(b) 1700 rpm

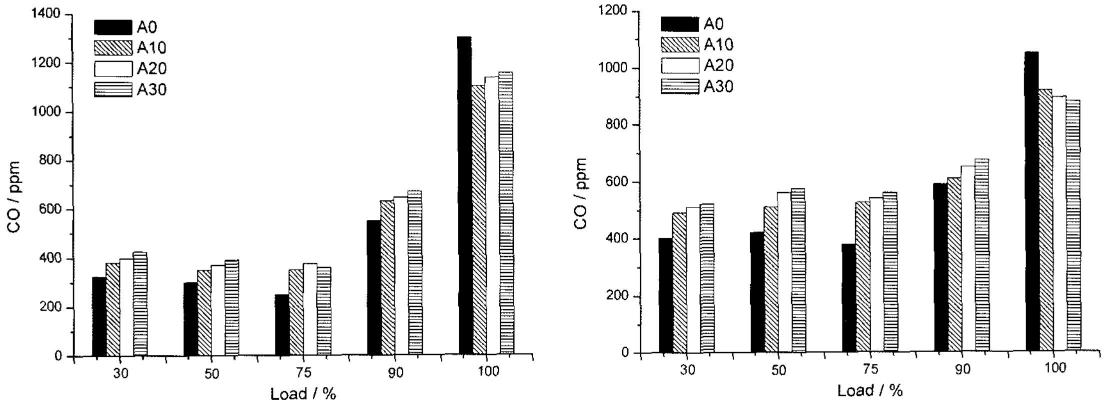
Figure 8. Effect of E-diesel on soot concentration.

high under low loads (Abu-Qudais *et al.*, 2000). However, under increasing loads, the temperature in the cylinder gradually rises, and as a result, the THC emission reduces. CO emission concentrations vary only a little under partial loads, but increase rapidly when the load rate is greater than 90%. This is considered to be related to the excess air ratio. NO_x emissions increase with the increases of the load, which is different from THC and CO emissions. As is well known, NO_x is formed under conditions of high temperatures, oxygen enrichment and long periods of high temperatures. Therefore, the longer ignition delay period of ethanol plus the rising flame temperatures due to the increase in load has increased the ratio of premixing fuel to



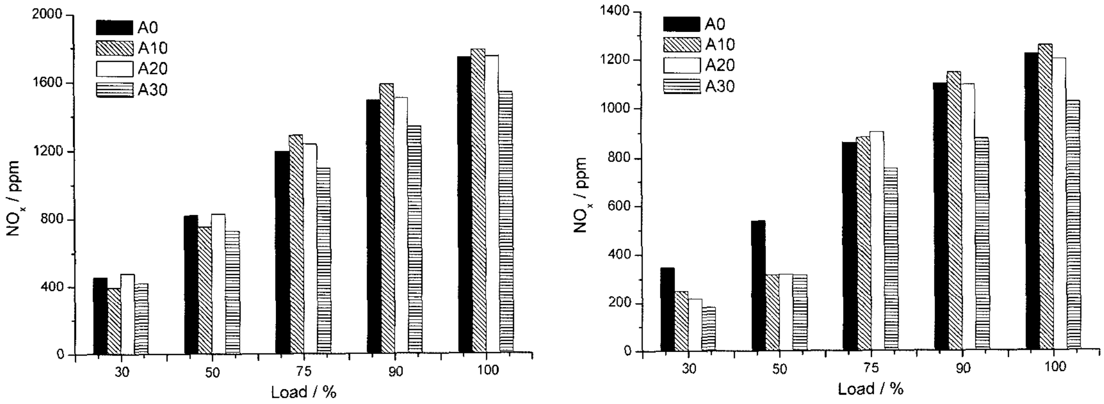
(a) 1200 rpm (b) 1700 rpm

Figure 9. Effect of E-diesel on THC emission.



(a) 1200 rpm (b) 1700 rpm

Figure 10. Effect of E-diesel on CO emission.



(a) 1200 rpm (b) 1700 rpm

Figure 11. Effect of E-diesel on NO$_x$ emission.

combusting fuel, which ultimately leads to greater NO$_x$ emissions.

It also can be found that, under low and medium loads, both the THC and CO emissions have an increasing trend with an increase in the ethanol blend ratio. This can be interpreted as the increase in ethanol content reducing the heat released during an operation cycle, and then lowering the flame temperature.

Under partial loads, the lower flame temperature can reduce the NO_x emissions; on the other hand, the longer ignition delay period and the oxygen content in ethanol will promote the generation of NO_x emissions. With the combined effects of these two factors, the ethanol content does not have much effect on the NO_x emissions. For high loads with the 30% ethanol blend ratio, it is obvious that NO_x emissions have been reduced by lower flame temperatures resulting from the high gasification latent heat of ethanol.

4. CONCLUSIONS

(1) An additive package consisting of alkyl alcohol, low ether, a macromolecule polymer and alkyl nitrate is designed. The ternary phase diagram shows that adding 1%~2% of the additive package can evidently improve the solubility of ethanol in diesel. The cold starting experiments show that the flammability of E-diesel containing the additive can be equivalent to that of neat diesel.

(2) The specific fuel consumption of E-diesel is more than that of neat diesel and is gradually increased with an increase in the ethanol blend ratio. If the ethanol blend ratio is less than 15%, the increased specific fuel consumption of E-diesel is not more than 5%, while its brake thermal efficiency is slightly more than that of neat diesel.

(3) The ignition delay period of E-diesel is prolonged with an increase in the ethanol blend ratio, but the combustion duration becomes shorter. This indicates that the addition of ethanol can promote the combustion of diesel fuel.

(4) With an increase in the ethanol blend ratio, the soot intensity of E-diesel gradually decreases. Even at medium or high loads, the soot intensity decreases by more than 50%, compared to neat diesel.

(5) Under the same ethanol blend ratio, with an increase in load, THC emissions decrease, CO emissions increase rapidly (at high loads), and NO_x emissions increase. On the other hand, under the same load, with an increase in the ethanol blend ratio, the THC and CO emissions increase, while at high loads, NO_x emissions evidently decrease.

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