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A Review of Research on Emission Characteristics of Ethanol-Diesel Blends in Diesel Engines

Meng Chen*

School of Mechanical Engineering/Institute of Vehicles and New Energy Technology, North China University of Water Resources and Electric Power, Zhengzhou City, Henan, China

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This paper reviews research on the emission characteristics of blended ethanol and other fuels. With the rapid development of modern industry, the extensive use of fuel engines has led to increasingly prominent contradictions between energy and the environment. In order to respond to sustainable development and reduce engine emissions in various countries, many scientific research institutions have conducted research on mixed fuels. The research of blended fuel mainly focuses on its sustainability, economy and environmental protection. Compared with gasoline engines, diesel engines have a lower fuel consumption rate and are widely used in heavy industry. But its fuel comes from refining crude oil, which is non-renewable and has poor cleanliness. As an emerging renewable fuel, ethanol is a fuel with good development prospects due to its good cleanliness, wide range of sources and renewable. If ethanol can be used as an alternative fuel for traditional internal combustion engines and diesel engines, it can save some traditional fuels and improve the emission problems of internal combustion engines to a certain extent. This paper introduces the research status of ethanol blended fuels, and the emission characteristics of engines (NO_x, HC and CO) under different ethanol ratios and different operating conditions. It can be seen that with the increase of ethanol blending ratio, NO_x content will increase, while CO and HC emissions will decrease.

Keywords: Ethanol; Diesel engine; Emission; Renewable

Introduction

With the rapid development of industrialization of human society, the consumption of traditional primary energy such as crude oil continues to increase. At present, the world's main primary energy sources are still oil, coal and natural gas, of which oil accounts for more than one-third of the total global energy consumption [1]. The current global energy structure is shown in Figure 1.

Countries around the world are facing the dual pressure of global warming and the depletion of oil resources caused by the greenhouse effect. Internal combustion engines are the main consumers of oil resources, consuming 60% of the world's oil. In addition, car ownership is growing rapidly year by year. China's oil consumption has increased year by year, and the dependence of oil on foreign countries has continued to increase [2]. China's limited oil reserves and heavy dependence on overseas imports have become important issues affecting China's energy security [3]. China's automobile growth and oil imports are shown in Figure 2. It can be predicted that with the further

**Corresponding author:* 1281665160@qq.com

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improvement of China's economic level, China's fuel consumption will still maintain a growth trend in the future.

Fig. 1. Composition of the world's energy architecture

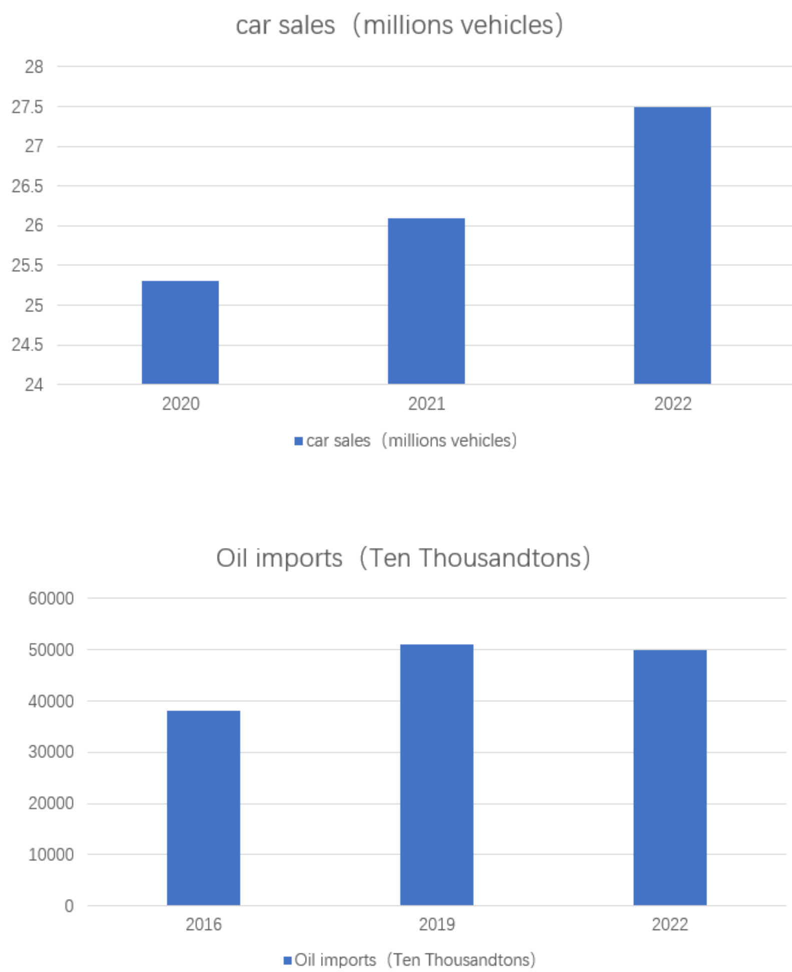

Fig. 2. China's automobile growth and oil imports

After more than 100 years of continuous development and progress, the internal combustion engine has been widely used in various fields with the advantages of high efficiency, low fuel consumption, strong environmental adaptability, simple structure and low failure rate [4]. Although new energy concepts are emerging in an endless stream, there is a tendency to overthrow the status of traditional internal combustion engines and replace them. However, the global internal combustion engine community and China's Ministry of Science and Technology still generally believe that the internal combustion engine will remain the most used engine in construction machinery, defense and military for a long time to come. In addition, the growing number of automobiles in addition have also increased the demand for primary energy such as oil. The huge production of vehicles also increases the burden on the environment, especially in commercial vehicles. Diesel engine has the characteristics of good thermal efficiency and economy, large torque and good durability, so it is widely used in large construction machinery and large passenger cars [5].

The combustion method of gasoline engine is mainly pre-mixed combustion, *i.e.,* the oil-gas mixture is formed outside the cylinder. The gas is sucked into the cylinder and then ignited by the spark plug. The gas burns to form a fire core, and then the surrounding mixed gas is sequentially ignited around the fire core. As the flame gradually expands, the temperature and pressure of the surrounding unburned mixed gas continue to rise, and the combustion gradually accelerates. The products produced after the combustion of gasoline are mainly CO, HC and NO_x.

The combustion method of diesel engine is mainly diffusion combustion. By compressing the air, the temperature of the air is higher than the ignition point of the fuel, thereby igniting the fuel. During the working process, diesel fuel will be sprayed into the combustion chamber in the form of a mist through the high-pressure oil pump, and the mist diesel fuel will continue to be mixed with the air in the cylinder after ignition by high-temperature gas. Due to the short formation time of the mixed gas, the concentration and temperature distribution of the mixed gas are uneven, and a part of the fuel oil cannot be completely burned under the condition of high temperature and lack of oxygen and is discharged with the exhaust gas, forming black smoke.

Generally speaking, diesel engines emit less CO and HC than gasoline engines, which are less than one-tenth of gasoline engine emissions. For NO_x, in the case of a large engine load, its emissions are not much different from the emission level of gasoline engines, while in the case of small loads, NO_x emissions will be lower than those of gasoline engines. In general, diesel engines emit CO, HC and NO_x below those of gasoline engine emission levels. However, the soot particles emitted by the diesel engine are much higher than the emissions of the gasoline engine, which is about 30~80 times the emission of the gasoline engine [6].

For the problem of motor vehicle exhaust pollution, most countries in the world have formulated relatively strict emission regulations. There are three mainstream motor vehicle emission standard systems in the world: Europe, the United States and Japan. At present, the European motor vehicle standard system is widely used because of its relatively loose testing requirements. Since 2000, China has formulated emission regulations suitable for China with reference to European automobile emission standards. China's Ministry of Environmental Protection has implemented "China VI-a" emission standards on July 1, 2020, while China VI-b Standard will be fully implemented by July 1, 2023. The China VI emission regulation has stricter restrictions on the regular emissions of vehicles than the China V emission regulation, which is also known as one of the strictest emission regulations. Table 1 shows a comparison of China V and VI emission regulations. The limit values in China VI is about 40-50% stricter than those of China V. The strictness of China VI is not only reflected in the values of these emissions, but also in the following three main aspects: First, the test cycle is different, from the New European Driving Cycle of China V to the Worldwide Harmonized Light Vehicles Test Cycle; Second, the test procedure requirements are different, and the quality requirements and road load settings of the test vehicle directly affect the fuel consumption and emission performance of the vehicle; Third, emissions testing has been transferred from the laboratory to the actual road for the first time compared to the previous stage of the emission regulations [5].

Table 1. Comparison of China emission regulations

Emission regulations and standards	China V	China VI	China VI B
CO(mg/km)	1000	700	500
THC(mg/km)	1000	100	50
NMHC(mg/km)	68	68	35
NO_x(mg/km)	60	60	35
PM(mg/km)	4.5	4.5	3.0
PN(p/km)	6×10^{11}	6×10^{11}	6×10^{11}

As a clean alternative fuel, ethanol plays an important role in alternative energy, reducing environmental pollution, and promoting related agricultural development. Its production of raw materials is diverse and sustainable, which can reduce human dependence on fossil fuels. As a liquid fuel, ethanol is easy to transport and use, and can be mixed with gasoline and diesel without major changes to the original engine. At the same time, as an oxygenated fuel, ethanol can theoretically reduce the emission of engine particulate matter and some harmful gases. Based on the above advantages, ethanol has been widely studied. China began to carry out ethanol pilot work in 2002, because its nature is close to gasoline. The current technology of applying ethanol fuel on gasoline engines has been quite mature. However, due to the large difference between the characteristics of ethanol and diesel itself, ethanol will be stratified for a long time after mixed with diesel. Due to the low cetane number of ethanol, it is not easy to compress and ignite. So, the practical application of ethanol in diesel engines is relatively small. But it is still a major topic for many scholars in recent years. China's diesel engine car ownership is large, and the total annual diesel consumption is about twice that of gasoline. Diesel resources are tight, so the study of the applicability of ethanol in diesel engine is still of great practical significance. Ethanol production by country is shown in Figure 3.

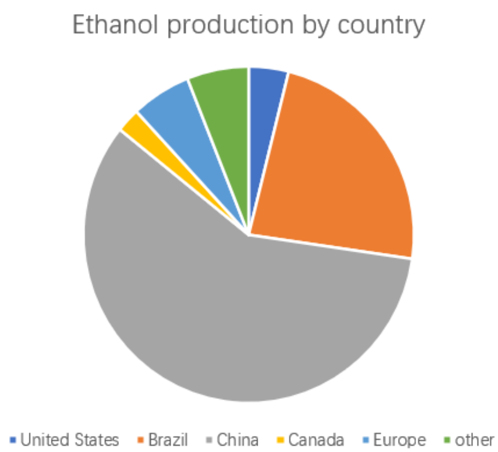

Fig. 3. Ethanol production by country

Ethanol Fuel Characteristics

Among the common biofuels, ethanol is the most widely used in combination with diesel fuel. Ethanol is a renewable fuel that can be made from residues from plants and crops and is also a typical oxygenated fuel. The comparison of the physical and chemical properties of ethanol, gasoline and diesel is shown in Table 2. It can be seen that the oxygen content of ethanol is as high as 34.8%. The high oxygen content can improve the area where the local mixture in the cylinder is too concentrated, and improve the quality of the mixture in the cylinder, thereby reducing the generation of soot. The latent heat of ethanol vaporization is 2.8 times that of gasoline and 3.2 times that of diesel, and the boiling point of ethanol is only 78℃. Compared with diesel and gasoline, it is easier to vaporize. The high latent heat of vaporization and low boiling point can not only improve the charge coefficient of the intake air and reduce the negative work of compression, but also reduce the maximum combustion temperature in the cylinder, achieve low-temperature combustion, and reduce the generation of NO_x. The activity of ethanol is relatively low compared with diesel and gasoline, and the research octane rating (RON) is as high as 108, and the low activity will inhibit the low-temperature exothermic process of diesel and delay the combustion process in the cylinder. The calorific value of ethanol is two-thirds that of gasoline or diesel. To get a fuel input of the same calorific value, ethanol has a third more mass than diesel.

Table 2. Comparison table of physical and chemical properties of three conventional fuels

Project	Ethanol	Diesel Fuel	Gasoline
Octane Number	108	20~30	70~90
Hexaoctane number	＜8	40~55	13~71
Auto-ignition temperature (℃)	426	≈250	420
boiling point (℃)	78	180~360	125.7
Latent heat of vaporization(KJ/kg)	826	250	297
Stoichiometric air-fuel ratio	9	14.3	14.8~15.1
Ignition limit (%)	4.3-19.0	1.4~7.6	1.0~6.0
Low calorific value (MJ/kg)	26.9	42.5~44.4	43.97
Density (g/mL)	0.725	0.86	0.679
Oxygen content (wt%)	34.8	0.2	0

As a renewable energy source, ethanol fuel comes from a wide range of sources. The general method of preparing ethanol is biological method. Ethanol fuel is obtained by fermentation using grain or crop straw as raw material. Another production method is synthesis, which produces ethanol by ethylene hydration reaction under certain conditions. So far, China's annual crop straw burning not only wastes energy but also pollutes the air. If these waste crops can be fully used for cellulosic ethanol production, both energy saving and environmental protection purposes can be achieved.

Emission Characteristics

NO_x Emissions

With the enhancement of environmental awareness, the national requirements for the emission of engine pollutants are getting stricter and stricter. High temperature, oxygen enrichment and combustion duration are the three main contributing factors to NO_x emissions. In order to study the effect of different ratios of ethanol-diesel blends on NO_x emissions, Luo [7] used YC6J180 diesel engine to measure NO_x emissions at different speeds and loads, and the results are shown in Table 3.

Table 3. NO_x emissions at different speeds and loads

Rotate speed (r/min)	Load (%)	NOx(ppm) E0	E10	E20
1200	25	498	691	680
1200	50	1095	1192	1290
1200	75	1481	1731	1814
1200	100	1792	2026	2273
1800	25	349	420	590
1800	50	765	855	959
1800	75	1087	1233	1339
1800	100	1324	1509	1699
2600	25	354	424	479
2600	50	621	727	819
2600	75	953	1064	1131
2600	100	1100	1285	1477

In order to more intuitively represent the emission comparison of NO_x under various conditions, the following comparison chart (Figures 4-6) is obtained based on the test data. The data shows that NO_x emissions from burning the same fuel increase with the load. It's believed that this is because NO_x emissions increase as the engine load increases, the maximum combustion temperature in the cylinder increases, and the combustion duration period becomes longer. At the same time, the NO_x emission concentration decreases with the increase of engine speed, because at high speed, the occupation time of each work cycle of the engine decreases, the fuel and gas mix poorly, and the combustion process deteriorates.

The water-cooled direct-injection diesel engine was used by Sun [8] to explore the impact of NO_x emissions from engines with different ethanol ratios. This study used a mixed fuel with mixed mass fractions of 10% and 20% ethanol, which were denoted as E10 and E20, respectively. The results are shown in Figure 7.

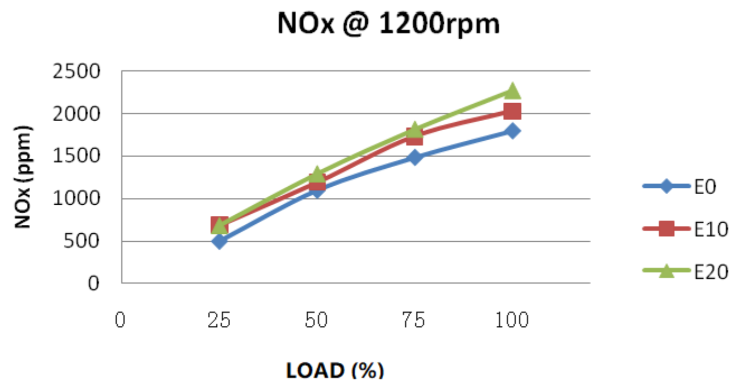

Fig. 3. Low engine NO_x emissions under different fuel mixing ratios

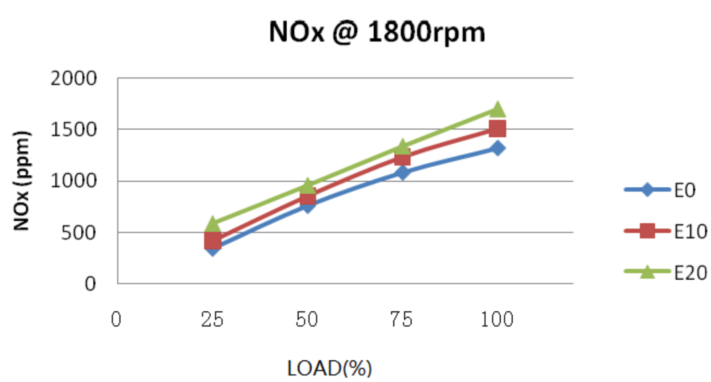

Fig. 4. Medium-speed NO_x emissions from engines at different fuel mixing ratios

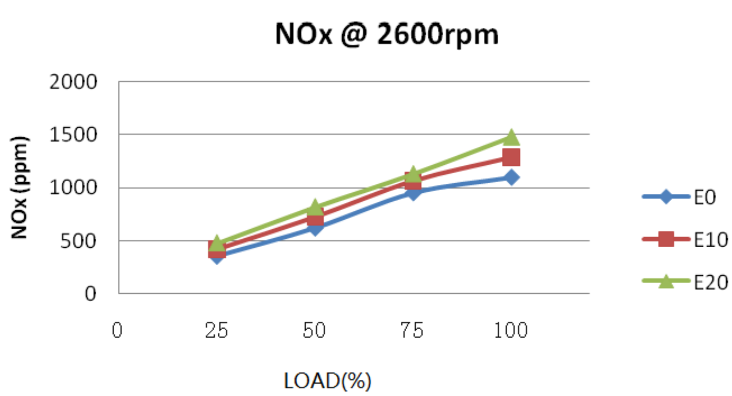

Fig. 5. High-speed NO_x emissions from engines under different fuel mixing ratios

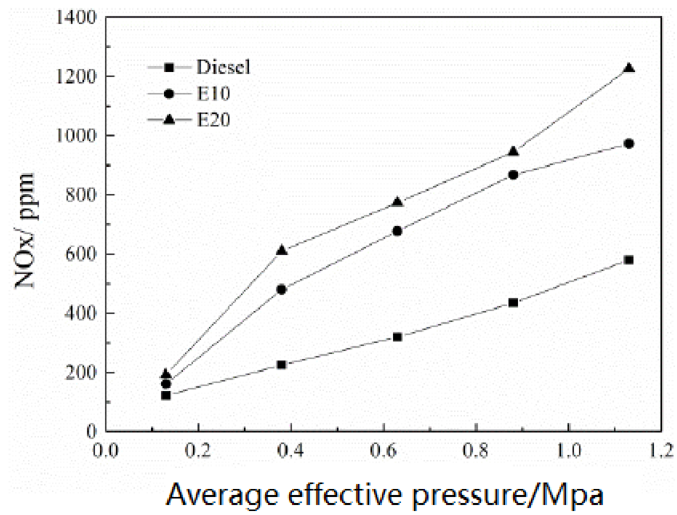

Fig. 6. Effect of ethanol addition ratio on NO_x emissions

The experimental results [8] show that NO_x emissions increase with the increase of ethanol addition. It can be seen from the figure that under low load, the addition of ethanol has little impact on the NO_x emissions of diesel engines. NO_x is mainly generated under high temperature, oxygen-rich conditions, under low load. Although the addition of ethanol will reduce the pressure and temperature in the cylinder, the amount of NO_x generation still increases slightly, which may be due to the addition of ethanol to make the fuel in the cylinder burn in an environment with a relatively high oxygen mass fraction compared with pure diesel, and eventually lead to a slight increase in NO_x production. Under medium and high load, the addition of ethanol increases the pressure and temperature in the cylinder, and the oxygenated ethanol provides oxygen-rich conditions for the combustion of the fuel, which finally increases the NO_x generation more obviously.

Yao *et al.* [9] found that under different working conditions, the fuel began to burn after the hysteresis period in the cylinder to produce NO_x. During combustion, the concentration of NO_x in the cylinder rises sharply, and then the fuel reacts chemically with the air and burns out. The concentration of NO_x in the cylinder tends to be stable and no longer changes until it is discharged through the exhaust duct. In this study, by exploring the effect of ethanol substitution rate on emissions under different operating conditions, it is shown that the maximum emission of NO_x in the combustion process of ethanol engines increases with the increase of ethanol replacement rate. It's believed this is because when burning pure diesel, only air enters the cylinder and not the ethanol/air mixture. The lag period is short, the temperature and pressure in the cylinder rise earlier, and the high temperature in the cylinder lasts longer. So, the amount of NO_x produced is less. With the increase of ethanol replacement rate, the amount of ethanol in the cylinder gradually increases, while the amount of diesel injection in the cylinder gradually decreases. The combustion temperature and pressure in the cylinder increase, the air flow movement in the cylinder is enhanced, the combustion duration is longer, and the combustion speed is faster, resulting in increased NO_x emissions. At the same time, the engine burns pure diesel with a shorter lag period than when adding ethanol combustion mode, so the NO_x generation time is earlier.

CO Emissions

CO is mainly produced by incomplete combustion of fuel. In order to study the effect of burning different proportions of ethanol diesel fuel blends on CO gas emissions. Luo [7] discussed the CO emissions of engines under different working conditions under different fuel mixing ratios. Finding that CO emissions are the least at medium speed and at medium load. The team believes that CO emissions rise sharply due to hypoxia caused by insufficient mixing of some fuel and air near full load, and that gas movement in the combustion chamber is too weak when diesel engine speeds are low. The mixture is unevenly formed, and there is more CO in the incomplete combustion product. At the same time, CO emissions decrease as the amount of ethanol in the fuel increases. Because ethanol is used as an oxygen-containing additive, it increases the oxygen content in the cylinder and also improves the uniformity of oxygen to a certain extent. This contributes to the reduction of CO emissions. In general, when the oxygen in the cylinder is sufficient and the gas is mixed evenly, it is conducive to reducing the emission concentration of CO.

Zhao [10] discussed the effect of ethanol ratio on CO emissions of dual-fuel dual-injection system under different working conditions. The results showed that with the increase of methanol, CO emissions of 0.2 MPa, 0.6 MPa and 1 MPa decreased first and then increased. The turning point for $R_{ethanol}$ was 80%. 40% and 60%, respectively. CO emissions decrease first with the increase of $R_{ethanol}$, because ethanol's higher laminar flame velocity, higher oxygen content and lower carbon content can accelerate the combustion process and make combustion more sufficient. Although further increasing $R_{ethanol}$ after the turning point will increase the oxygen content in the mixture, it will also lead to the phenomenon of pool fire near the intake valve, and a large amount of fuel accumulates near the intake valve to form a local concentration area of fuel, which is not conducive to full combustion of fuel, resulting in increased CO emissions.

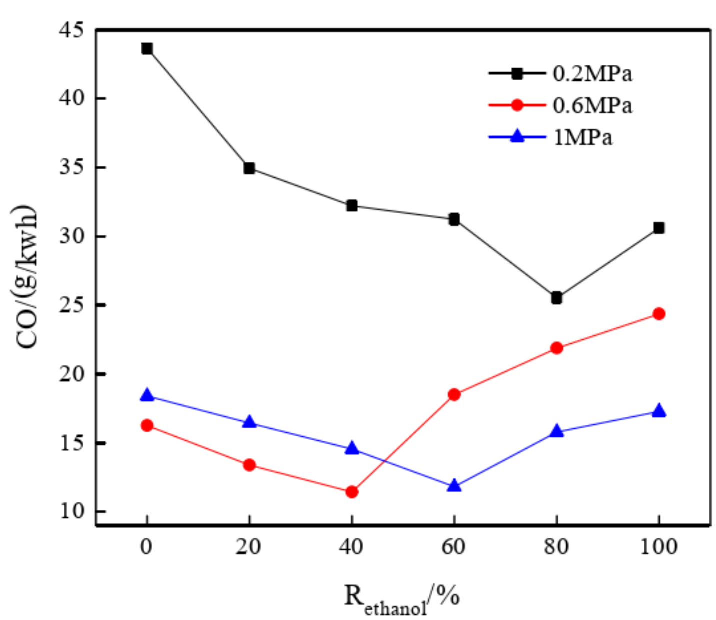

Fig. 7. CO emissions vary with $R_{ethanol}$ under each load

Li *et al.* [11] found through combustion tests that the blending of ethanol will reduce the power of diesel engines, increase the fuel consumption rate, and have lower CO emissions in a wide range of working conditions.

Wang and Tian [12] found that under the premise of maintaining the original parameters and structure of diesel engines, with the increase of the proportion of ethanol in the mixed fuel, the emission of soot and CO has improved significantly.

Britto and Martins [13] modified a single-cylinder diesel engine to achieve Reactivity Controlled Compression Ignition (RCCI) combustion of ethanol premix injection in the intake tract, and studied the impact of different ethanol replacement rates on diesel engine emissions. The results show that ethanol can achieve the best substitution rate when the injector flow rate is high and the vortex flow structure is high, and the NOx generation in the engine exhaust can be reduced under this working condition. But the generation of HC and CO exhaust pollutants is increased.

HC Emissions

HC gas emissions are produced due to incomplete combustion of fuel. Because the engine adopts the combustion method of injection fuel in the cylinder, it will lead to the fuel and air can not become completely uniform mixture. The mixture gas is locally too concentrated or too diluted, and the mixed gas near the cylinder wall will be affected by the cold shock effect. So, the fuel combustion is insufficient, resulting in HC emissions. In addition, fuel in the cylinder liner and piston clearance is less likely to participate in combustion, which is one of the reasons for the generation of HC emissions. Luo [7] separately explored the HC emissions of the engine under different working conditions and different fuel mixing ratio. It's found that with the increase of engine load, the temperature in the cylinder increased, which was conducive to fuel combustion. Compared with the HC emission concentrations of different fuels, HC emissions decreased with increasing ethanol content in fuels. Because ethanol is added to the fuel, the oxygen content increases, which promotes fuel combustion, thereby reducing HC emissions. The speed of the engine does not have much effect on HC emissions. Zou [14] explored the effects of ethanol replacement rates on engine emission characteristics under specific working conditions under an altitude of 1972 m and an ambient temperature of 20°C, when the ethanol replacement rate was selected as 0%, 10%, 20%, 30% and 40%, respectively. The results are shown in Figure 9.

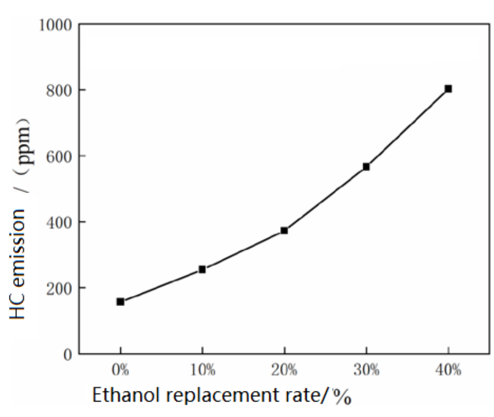

Fig. 8. Emission of HC

It can be seen from the figure that the HC emission generation after the introduction of ethanol combustion is higher than that of the original diesel engine, and the HC generation increases with the increase of ethanol replacement rate. After introducing ethanol combustion, when the intake valve is opened, the premixed homogeneous mixture quickly fills all corners of the combustion chamber. Examples include the gap between the top bank of the piston and the cylinder wall and the valve clearance that flame propagation cannot reach. Because the overall temperature in the cylinder is reduced and the quenching effect on the wall facing the flame is enhanced, the emission of HC is higher than that of pure diesel.

Morsy [15] used the fumigation method to carry out secondary injection with ethanol in the diesel engine, and the results showed that the emissions of NO, CO and HC were increased. Gnanamoorthi and Devaradjane [16] studied the effects of different ethanol blending ratios on diesel engines under different compression ratios. The results show that under the condition of testing the maximum compression ratio, the mixing of ethanol will increase the thermal efficiency of the diesel engine. At other compression ratios, the thermal efficiency decreases when ethanol is added beyond a certain range. The addition of ethanol delays ignition at different compression ratios, and the delay becomes more pronounced as the proportion of ethanol increases. At the same time, the addition of ethanol will significantly reduce HC, CO and soot.

CONCLUSIONS

Ethanol diesel is an alternative fuel to traditional diesel, and the production of diesel fuel by adding ethanol can effectively alleviate the shortage of petroleum resources caused by relying solely on traditional petroleum resources to produce diesel. At the same time, ethanol diesel can significantly reduce the emission of soot and particulate matter after combustion, and reduce the pollution to the environment.

In summary, several conclusions can be drawn as follows：

1. The increase of the proportion of ethanol in diesel fuel will increase the emission of NO_x, especially under large-load conditions. But in the case of low load, the emission growth of NO_x is less, and appropriately reducing the advance angle of fuel supply is conducive to improving engine thermal efficiency and reducing emissions.
2. The mixing of ethanol with diesel will reduce the power of the diesel engine. When the oxygen in the cylinder is sufficient and the gas is evenly mixed, the increase of ethanol content is beneficial to reduce the concentration of CO emission.
3. The emission of HC and CO from ethanol/diesel blends is related to the proportion of ethanol and engine conditions, and the proportion of ethanol in ethanol diesel fuel should not be too large from the comprehensive consideration of engine performance and emissions. Under the condition that the thermal efficiency of E20 is comparable to that of the original engine, the emission of HC, CO and NO may be reduced to a certain extent.
4. However, due to the difference in structure and properties, the compatibility of ethanol diesel is poor, and the addition of co-solvent to ethanol/diesel would increase the production cost of diesel. These factors hinder the promotion and application of ethylene/diesel blends to varying degrees, so the focus of

ethanol/diesel blends research in the future should be to develop efficient and economical co-solvents to reduce the cost of ethanol diesel. At the same time, when using ethanol diesel, technical measures to reduce NO_x should also be taken to reduce environmental pollution to a greater extent.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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