Hindawi Publishing Corporation
Journal of Biomedicine and Biotechnology
Volume 2011, Article ID 417421, 10 pages
doi:10.1155/2011/417421

Research Article

Performance and Emission Characteristics of Diesel Engine Fueled with Ethanol-Diesel Blends in Different Altitude Regions

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Received 11 June 2010; Revised 5 October 2010; Accepted 8 November 2010

Academic Editor: Andrei Surguchov

In order to investigate the effects ethanol-diesel blends and altitude on the performance and emissions of diesel engine, the comparative experiments were carried out on the bench of turbo-charged diesel engine fueled with pure diesel (as prototype) and ethanol-diesel blends (E10, E15, E20 and E30) under different atmospheric pressures (81 kPa, 90 kPa and 100 kPa). The experimental results indicate that the equivalent brake-specific fuel consumption (BSFC) of ethanol-diesel blends are better than that of diesel under different atmospheric pressures and that the equivalent BSFC gets great improvement with the rise of atmospheric pressure when the atmospheric pressure is lower than 90 kPa. At 81 kPa, both HC and CO emissions rise greatly with the increasing engine speeds and loads and addition of ethanol, while at 90 kPa and 100 kPa their effects on HC and CO emissions are slightest. The changes of atmospheric pressure and mix proportion of ethanol have no obvious effect on NO_x emissions. Smoke emissions decrease obviously with the increasing percentage of ethanol in blends, especially atmospheric pressure below 90 kPa.

1. Introduction

Recently, diesel engine has received considerable attention because of its high heat efficiency and low emission; however, with the stringent emission standard and limited petroleum reserve, alternative fuels for diesel engine have been used. As a renewable and oxygen-containing biofuel, ethanol is a prospective fuel for vehicle, which can be blended with diesel or be injected into cylinder directly. There are many studies on the application of ethanol on diesel engine, which focus on the three aspects: application techniques of ethanol on diesel engine, fuel properties of ethanol-diesel blends, and effects on the combustion and emission characteristics of ethanol-diesel blends [1–6].

Because ethanol is polar molecule and its solubility in diesel is prone to be affected by temperature and water content, high percentage addition of ethanol to diesel is difficult, especially under low temperature (below about 10°C). In order to mix ethanol and diesel, an emulsifier or cosolvent should be added. Many literatures indicated that aromatic hydrocarbon, middle distillate, and wax content of diesel are important factors of its blend with ethanol [1, 2]. Presently, the application techniques of ethanol on diesel engine can be divided into the following four classes: (1) ethanol-diesel blend by high-pressure pump [3], (2) ethanol fumigation to the intake air charge by using carburetion or manifold injection, which is associated with limits to the amount of ethanol due to the incipience of engine knock at high loads, and prevention of flame quenching and misfire at low loads [3–6], (3) dual injection system requiring an extra high-pressure injection system and a related major design change of the cylinder head [6, 7], and (4) blends of ethanol and diesel fuel by using an emulsifier or cosolvent to mix the two fuels for preventing their separation, requiring no technical modifications on the engine side [6, 8, 9].

The physical and chemical characteristics of ethanol-diesel blends are very important to its application on diesel engine. The stability, density, viscosity, surface tension, specific heat, heat value, and cetane number of blends have great impact on the injection, atomization, ignition, and combustion properties, as well as cold start, power, fuel consumption, and emission characteristics of engine. Additionally, the poking and leakage of conventional tank, fuel pipe, and sealing part can be rendered. More stringent demands are necessary for the mixture, transportation, storage, and usage of fuel because of low flash point of ethanol-diesel blends [9–13].

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. According to research carried out by Li et al. [12], each 10-vol% ethanol added to the diesel fuel, results in a 7.1-unit reduction in cetane number of the resulting blend. References [8, 14, 15] indicated that the addition of ethanol resulted in increased ignition delay, reduced combustion duration, high maximum pressure rates, and slightly decreased gas temperature because of its low cetane number and high/low heat value. With the addition of cetane number improver, the combustion properties can reach the level of prototype at middle-high load.

Without modification, the ethanol-diesel blends decreased the power of diesel engine and increased the brake-specific fuel consumption; however, the performance of prototype can be rehabilitated after adjusting the fuel delivery and injection timing of engine [16–18]. Reference [19] showed no significant power reduction in the engine operation on different blends of ethanol-diesel (up to 20%) at a 5% level of significance. Brake-specific fuel consumption increased by up to 9% as compared to diesel alone. The exhaust gas temperature and lubricating oil temperatures were lower with operations on ethanol-diesel blends as compared to operation on diesel.

Ethanol-diesel blends can reduce the smoke and PM emissions of diesel engine. The higher this reduction is, the higher the percentage of ethanol is in the blends. The reason is that the oxygen content in blends can promote the combination of fuel and oxygen, even in fuel-rich region [16, 20–22]. The NOx emissions remained the same or very slightly reduced with the use of the ethanol-diesel fuel blends with respect to those of the diesel; however, the NOx emissions can be reduced by other techniques, such as EGR and SCR. The hydrocarbons (HCs) emissions were increased with the use of ethanol-diesel blends. The higher this increase is, the higher the percentage of ethanol in the blend, however, the HC emissions of blends can still meet the emission standards due to low HC emissions of diesel engine. References [12, 20] showed that the CO emissions of ethanol-diesel blends were increased at low load and were decreased at high load. Additionally, the CO_2 emissions were decreased due to the low C/H ratio of ethanol-diesel blends.

The irregular emissions of diesel engine were also affected by the addition of ethanol. Cheung et al. [23] reported that the unburned ethanol and acetaldehyde increased when a 4-cylinder direct-injection diesel engine was fueled with ethanol-diesel blends, but formaldehyde, ethene, ethyne, 1,3-butadiene, and BTX (benzene, toluene, and xylene) in general decreased, especially at high engine load. A diesel oxidation catalyst (DOC) is found to reduce significantly most of the pollutants, including the air toxics. Song et al. [24] showed that the content of 16 kinds of PAHs and DNA damage level decreased in exhaust of E5 compare with that of diesel.

The atmospheric pressure and air density can affect the combustion process of engine, so the power performance, fuel consumption, and emission characteristics of engine will be different when the engine was run at different altitudes. So far, the application researches of ethanol-diesel blends were almost carried out at low altitude. Therefore, in order to investigate the effects of ethanol-diesel blends on the performance and emissions of diesel engine under different atmospheric pressures, the comparative experiments were done between the engine fueled with pure diesel (as prototype) and ethanol-diesel blends at different altitudes [25–27].

Table 1: Engine Configuration.

Type	In-line, 4 cylinders
Bore × stroke (mm)	100 × 105
Displacement (L)	3.298
Combustion chamber	ω-type direct injection
Induction system	Turbocharged and intercooler
Compression ratio	17.5 : 1
Rated power $(kW/(r\cdot min^{-1}))$	73/3200
Maximum torque $(N\cdot m/(r\cdot min^{-1}))$	245/2200

2. Materials and Methods

2.1. Test Engine. The test engine was a 3.298 L, direct-injection, turbocharged diesel engine. The relevant characteristic of detailed engine configuration was given in Table 1. During experiment the engine was tested without any modification.

2.2. Emission Test Apparatus and the Realization of Different Atmospheric Pressures. The emission test devices included an AC electric dynamometer (AVL AFA Drive 250/4–8), an exhaust analyzer (AVL CEB), a fuel consumption meter (AVL 733), and a smoke meter (AVL 415). The altitude of test bench is 1912 m, and the local atmospheric pressure is 81 kPa. The relative humidity is 40 ∼ 60%, and temperature ranges from 18°C to 21°C.

The different atmospheric pressures were produced by an engine condition system (AVL ACS1300/300), which can automatically controls the atmospheric pressures and inlet gas temperatures. The inlet of turbocharger compressor was connected to the pressure output of engine condition system, and the pressure sensor and temperature sensor were used. When the *c* was 81 kPa, the exhaust back pressure was set at local environmental pressure. When the atmospheric pressure was 90 kPa or 100 kPa, the back pressure of engine was adjusted to inlet pressure [17, 18].

2.3. Blend of Ethanol and Diesel. A hydraulic vibration emulsification device was developed, which was installed on the high-pressure pump of diesel engine. The ethanol and diesel were delivered to the emulsification device by two fuel delivery systems. The emulsified ethanol/diesel was injected into the cylinder by pump and injector. The emulsification device can provide different proportions of ethanol and diesel without modifying engine and stopping

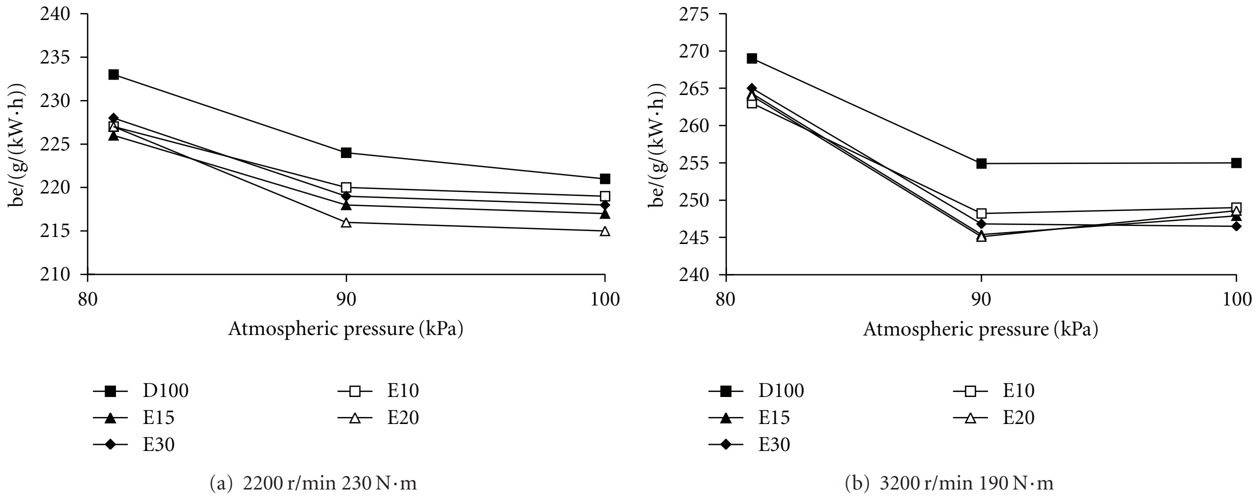


Figure 1: Effects of different atmospheric pressure and mix proportion on equivalent BSFC.

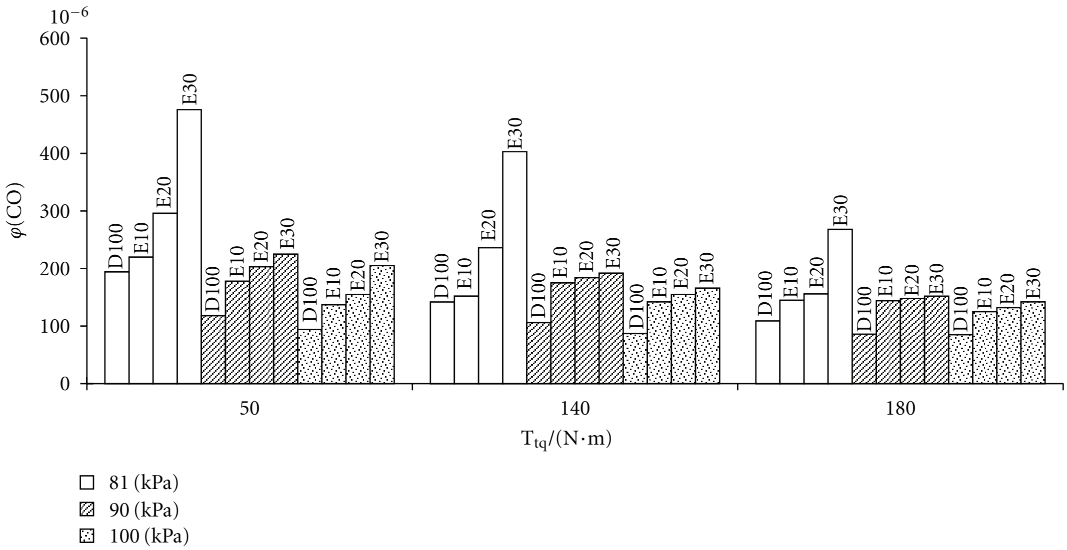


Figure 2: Comparison of HC emission of different atmospheric pressure and mix proportion at speed 1400 r/min.

engine. The emulsification device can use the 95% ethanol without any emulsifier and surfactant. The test diesel is $0^{\#}$ diesel [5].

3. Results and Discussions

3.1. Analysis of Engine Performance. The low heat value (Qi) of ethanol is lower than that of diesel, so it is necessary to consider the effect of heat value when making comparison of brake-specific fuel consumption (BSFC) and then to refer to equivalent BSFC (b_e), defined as $b_e = \text{BSFC} * Q_{ie}/Q_{id}$. Q_{ie} and Q_{id} are the low heat value of ethanol-diesel blends and diesel, respectively. Figure 1 illustrated the comparison of equivalent BSFC under three atmospheric pressures.

It can be seen that b_e of ethanol-diesel blends are lower than those of diesel. The ethanol is an oxygenated fuel with lower surface tension and boiling point, so the fast vaporization of ethanol can promote the spray performance and the formation of mixture gas, which is good for the premix and diffused combustion. Additionally, the higher oxygen content of ethanol can increase the excess air ratio and improve the heat efficiency. On the other hand, the decrease of b_e was not proportioned to the addition of ethanol. Compared to diesel, E10 reduced b_e by 1.0 ∼ 2.6%, while E15 by 1.8 ∼ 3.0%, E20 by 2.6 ∼ 2.7%, and E30 by 1.4 ∼ 2.1%. The results indicated that E15 and E20 had better performance than E10 and E30 because E10 has lower proportion of ethanol and E30 maybe has bad emulsification.

It can be seen that b_e of both ethanol-diesel blends and diesel are decreased with the increase of atmospheric pressure. The reduction of b_e was great when atmospheric pressure changed from 81 kPa to 90 kPa, while the reduction was slight when atmospheric pressure changed from 90 kPa to 100 kPa.

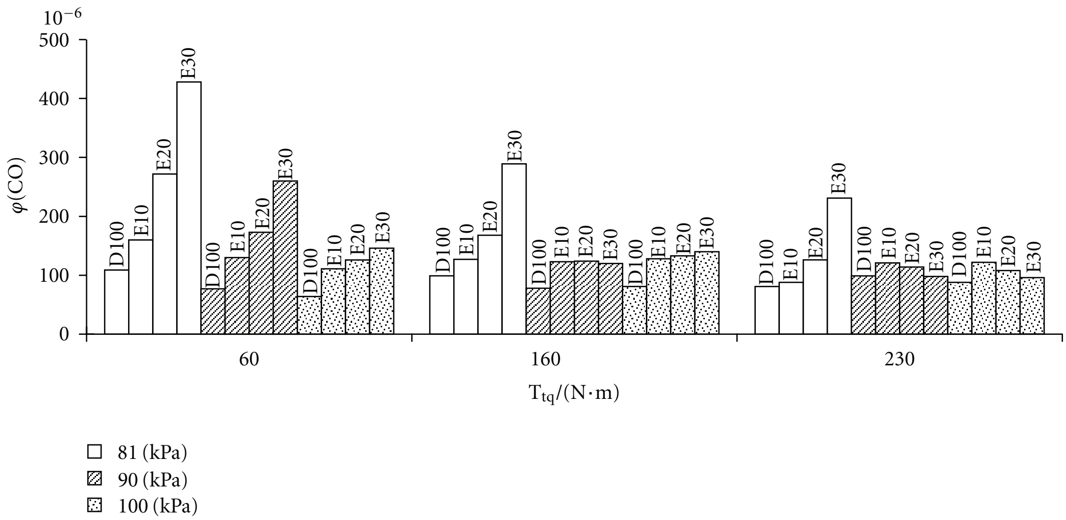


Figure 3: Comparison of HC emission of different atmospheric pressure and mix proportion at speed 2200 r/min.

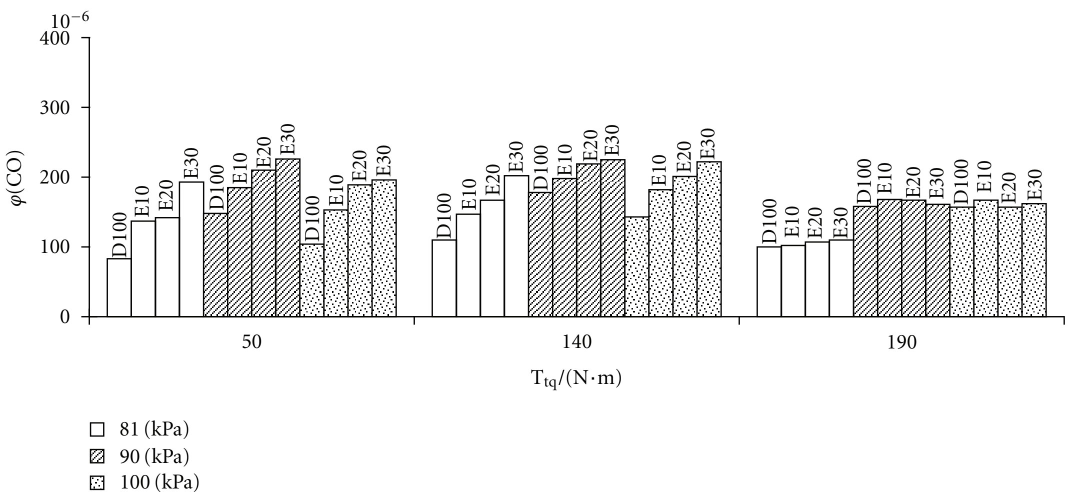


Figure 4: Comparison of HC emission of different atmospheric pressure and mix proportion at speed 3200 r/min.

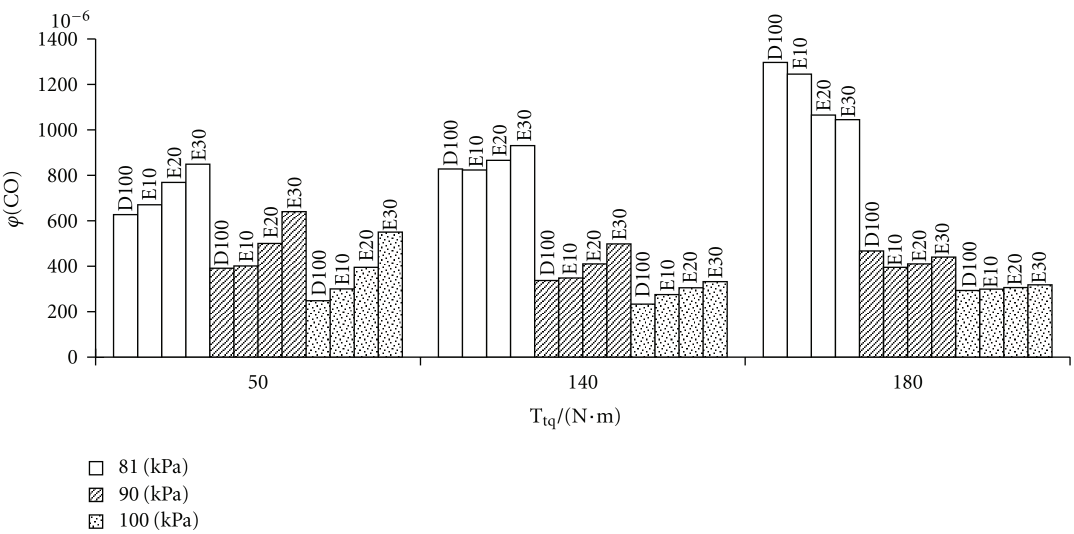


Figure 5: Comparison of CO emission of different atmospheric pressure and mix proportion at speed 1400 r/min.

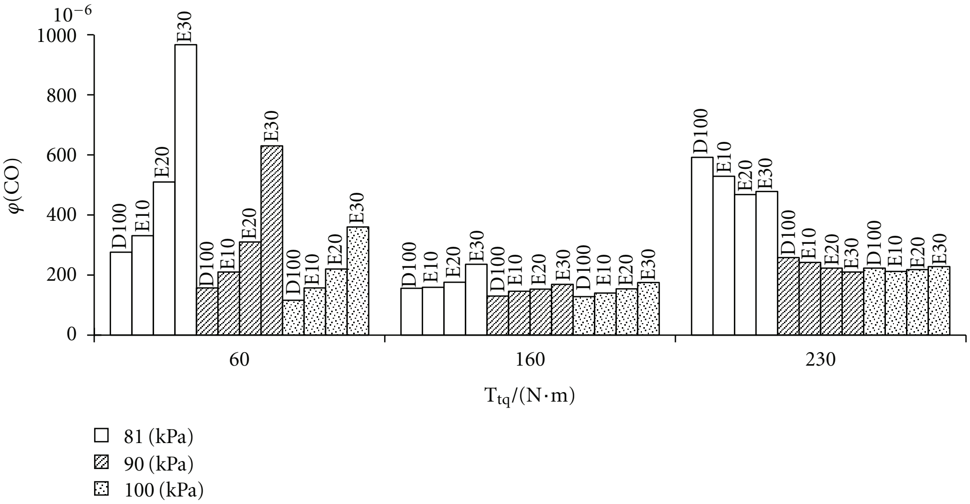


Figure 6: Comparison of CO emission of different atmospheric pressure and mix proportion at speed 2200 r/min.

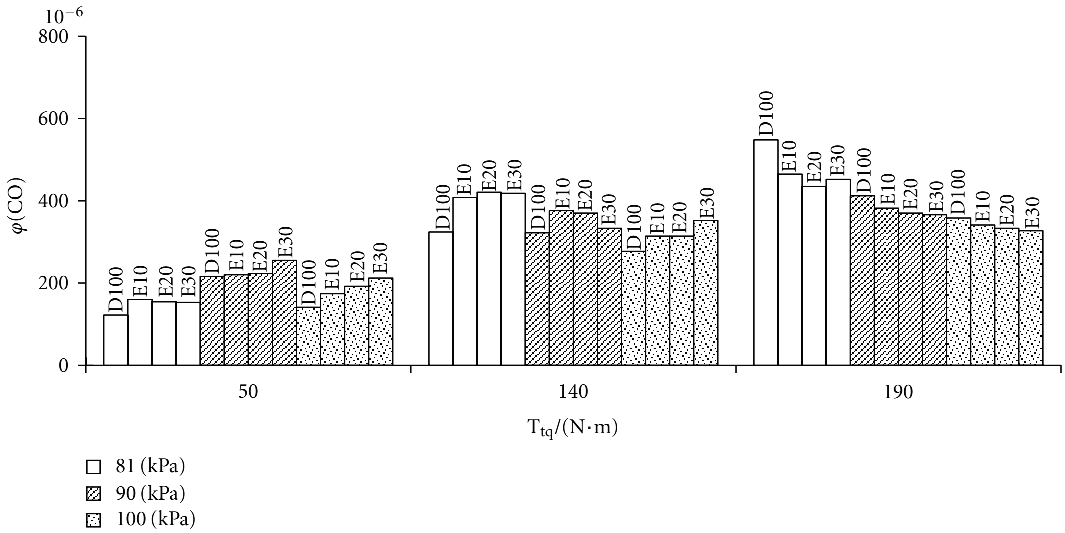


Figure 7: Comparison of CO emission of different atmospheric pressure and mix proportion at speed 3200 r/min.

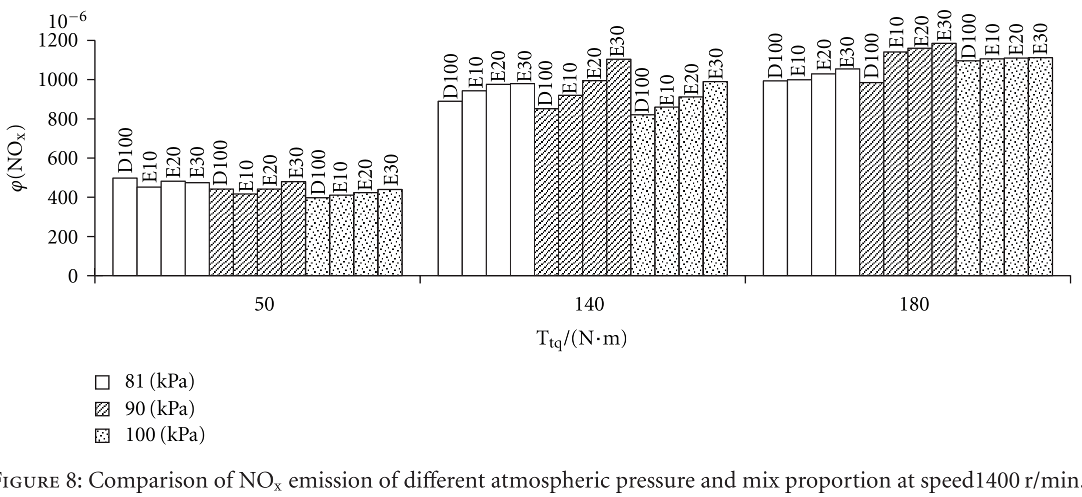


Figure 8: Comparison of NO_x emission of different atmospheric pressure and mix proportion at speed1400 r/min.

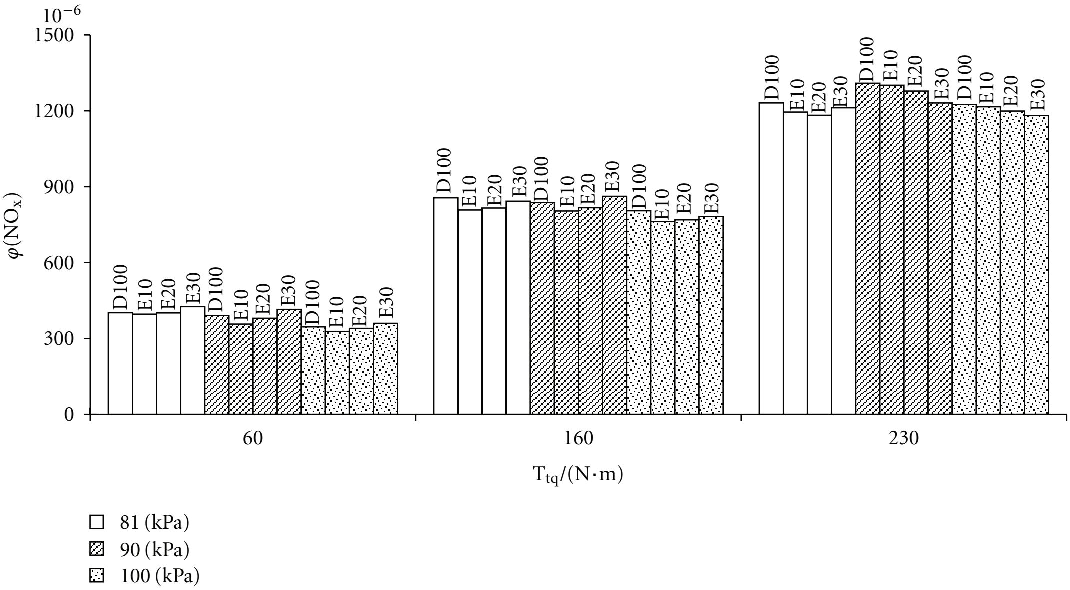


FIGURE 9: Comparison of NO_x emission of different atmospheric pressure and mix proportion at speed 2200 r/min.

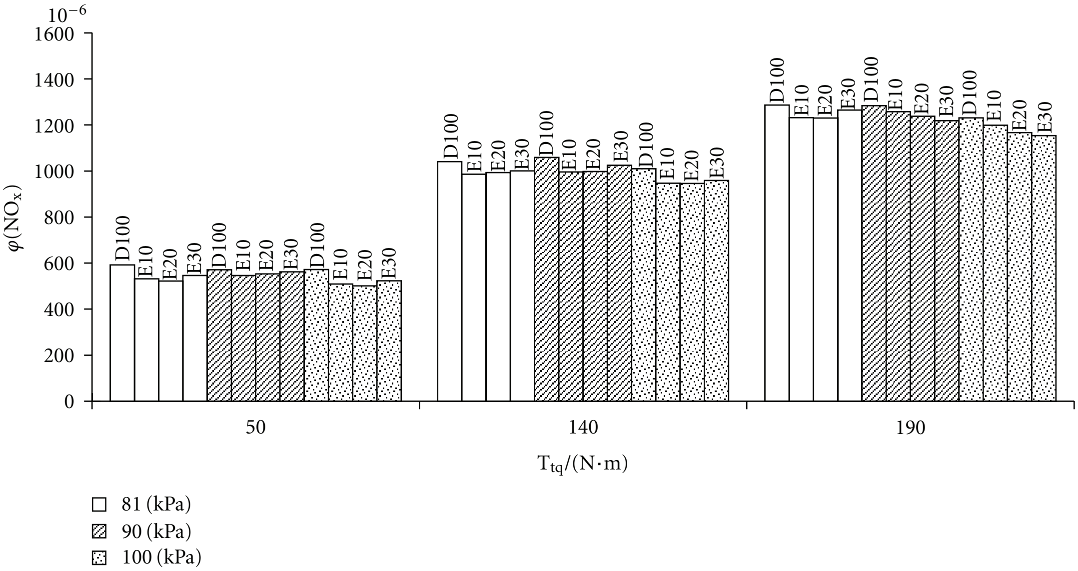
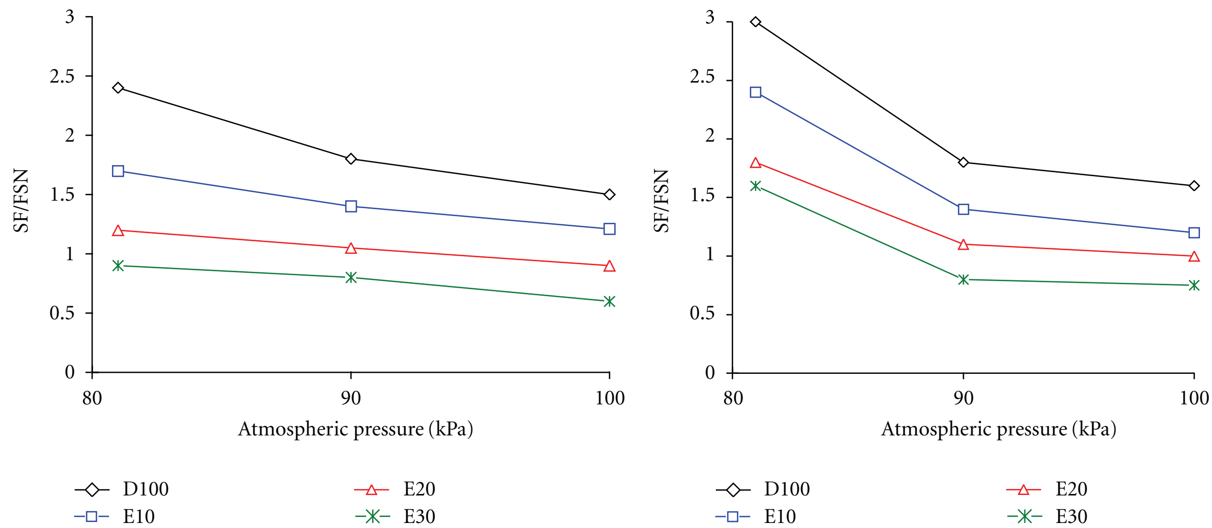


FIGURE 10: Comparison of NO_x emission of different atmospheric pressure and mix proportion at speed 3200 r/min.

3.2. Emission Characteristics of HC. The HC emissions of diesel-ethanol blends under three atmospheric pressures were shown in Figures 2, 3, and 4. It can be seen that the HC emissions under different atmospheric pressures show significant divergences when the mix proportions, engine speeds, and loads change. With increasing speeds and loads, the effect of atmospheric pressure on HC emission was not significant. At 2200 r/min and 81 kPa, the mix proportions had great effects on the HC emissions, especially at light load (50 N·m), which rendered the increase by 47% ~ 293%. The increase of HC emissions of E30 was great. The HC emission increased with the increasing percentage of ethanol in blends; however, the HC emissions of ethanol-diesel blends nearly reached the level of prototype at 3200 r/min.

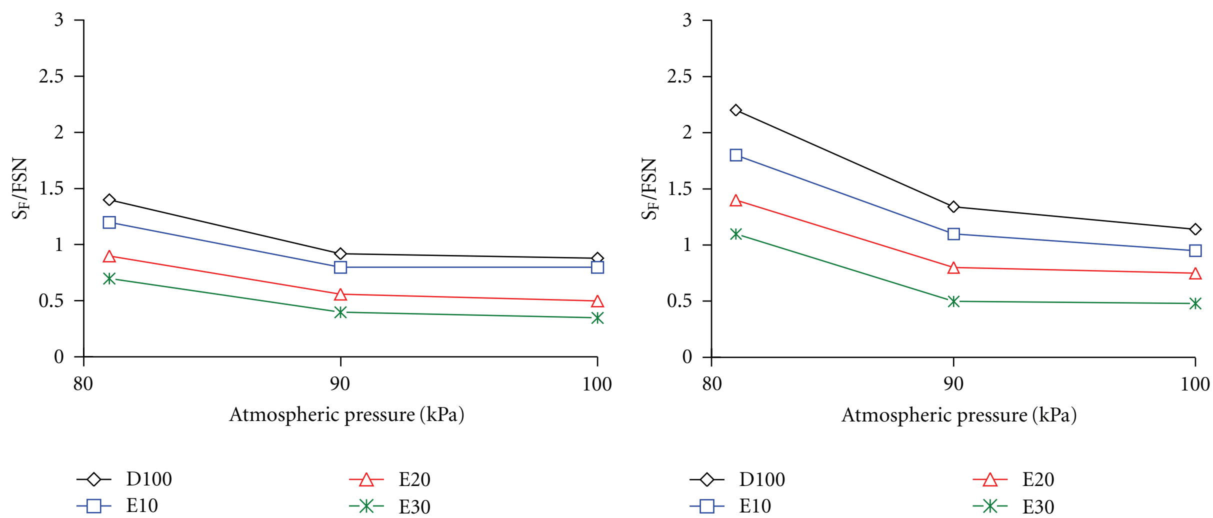
Because the ethanol has higher latent heat of vaporization, which reduces the gas temperature and promotes the chilling of cylinder wall, the HC emission rises evidently with the increasing content of ethanol at low speed and load of engine. When engine speeds and loads go up, the temperature of gas and combustion chamber wall increases, which accelerates the formation of mixture gas and promotes the combustion of fuel, so the increasing blends of ethanol has litter influence on the HC emissions at higher engine speed and load. Thus, HC emission had slight increase and reached the level of diesel-fueled engine at some engine loads. Due to its higher latent heat of vaporization and lower cetane number, higher proportion of ethanol reduces the gas temperature and retards the ignition delay, which



(a) 1400 r/min 140 N·m

(b) 1400 r/min 180 N·m

Figure 11: Comparison of smoke of different atmospheric pressure and mix proportion at speed 1400 r/min.



(a) 2200 r/min 160 N·m

(b) 2200 r/min 230 N·m

Figure 12: Comparison of smoke of different atmospheric pressure and mix proportion at speed 2200 r/min.

results in the significant rise of HC emissions of E30 at lower speed and load. Additionally, the limited emulsifiable ability of mixture device at higher proportion of ethanol may be another reason. Based on the above analysis, it can be said that HC emissions of ethanol-diesel blends are depended on the engine speed, load, and the mix proportion of ethanol.

3.3. Emission Characteristics of CO. The CO emissions of ethanol-diesel blends under three atmospheric pressures were shown in Figures 5, 6, and 7. At 2200 r/min and low load (50 N·m), E10, E20, and E30 augmented the CO emissions by 20% ~ 250%, 33% ~ 301%, and 35% ~ 210%, respectively. With increasing engine speed and engine load, atmospheric pressure had litter influence on the CO emission. At low and middle loads, the higher proportion of ethanol increased the CO emission slightly. At full load, CO emissions of ethanol-diesel blends were lower than those of pure diesel, especially at 81 kPa. The experimental results indicated that the ethanol-diesel blends would not deteriorate the CO emissions except for 2200 r/min and low load.

The addition of ethanol causes the reduction of gas temperature, which restrains the oxidation of CO, so CO emission goes up at low load. With the increase of engine speed and load, the increase of gas temperature, wall temperature, and oxygen content of ethanol promote the oxidation condition of CO, which decreases the negative effect of addition of ethanol. At full load, the excess air ratio is comparatively low, so the increasing proportion of ethanol decreases the CO emission greatly. With the increase

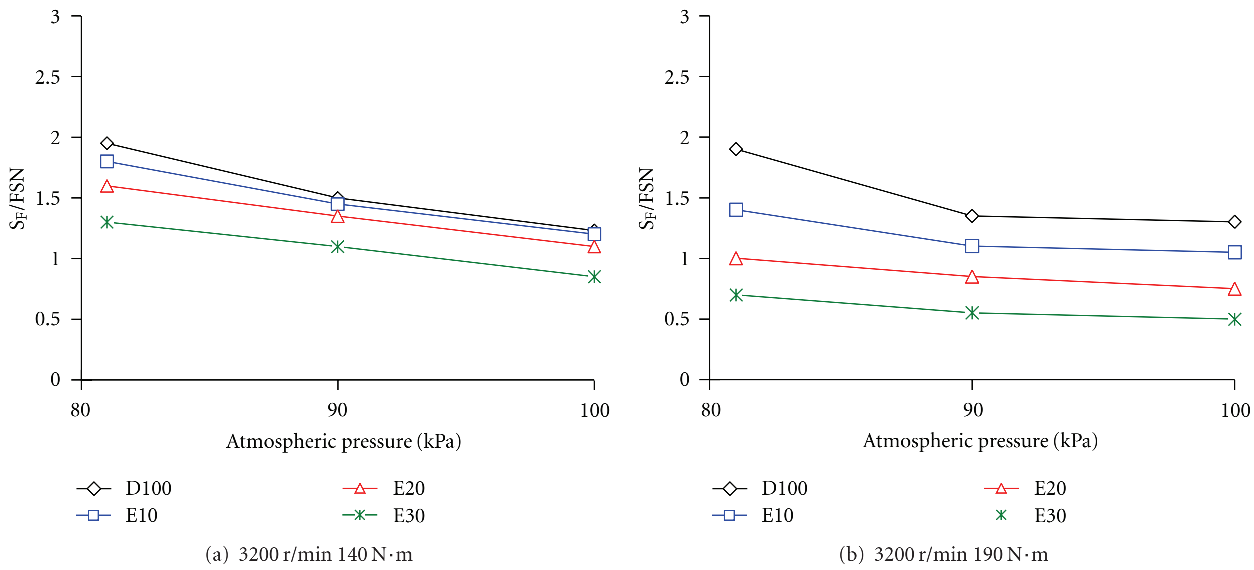


Figure 13: Comparison of smoke of different atmospheric pressure and mix proportion at speed 3200 r/min.

of atmospheric pressure, the excess air ratio increases and the effect of ethanol is weakened, so the influence of atmospheric pressure on the CO emission is slight. Based on the above analysis, it can be said that CO emissions of ethanol-diesel blends are depended on the engine speed, load, and the mix proportion of ethanol.

3.4. Emission Characteristics of NO_x. Figures 8, 9, and 10 showed the NOx emissions of ethanol-diesel blends under three atmospheric pressures. At different atmospheric pressures and mix proportions, the NOx emissions showed the similar trend. The ethanol-diesel blends reduced the NOx emission at most modes. At 1400 and 2200 r/min and low load, the slight increase of NOx emission for E30 should be rendered by the bad emulsification at higher mix proportion. The increasing oxygen content can promote the formation of NOx; however, the maximum gas temperature is the most important factor of NOx formation, so the decreased gas temperature caused by higher latent heat of vaporization of ethanol can reduce the NOx emission.

3.5. Emission Characteristics of Smoke. Figures 11, 12, and 13 showed the smoke emissions of ethanol-diesel blends under three atmospheric pressures at full load. At different atmospheric pressures, the smoke emissions of ethanol-diesel blends had similar tendency as those of diesel. The smoke emissions of both blends and diesel were decreased with the increasing atmospheric pressures. Compared with pure diesel, E10, E20, and E30 reduced the smoke emissions by 18% ~ 26%, 36% ~ 47%, and 50% ~ 63%, respectively, at 81 kPa, by 18% ~ 19%, 40% ~ 38%, and 63% ~ 59%, respectively at 90 kPa, and by 17% ~ 19%, 34% ~ 42%, and 58% ~ 62%, respectively, at 100 kPa. It showed that higher mix proportion of ethanol resulted in lower smoke emission at the same atmospheric pressure and load. At 2200 r/min when atmospheric pressure ranged from 81 kPa to 90 kPa the smoke emissions of E10, E20, and E30 were reduced by 39%, 43%, and 55%, respectively. However, when atmospheric pressure ranged from 90 kPa to 100 kPa, the smoke emissions of E10, E20, and E30 were reduced by 14%, 6%, and 4%, respectively. It can be seen that atmospheric pressure has significant effect on the smoke emission when atmospheric pressure is lower than 90 kPa. The influence is weakened when it is above 90 kPa.

The oxygen atom is usually connected to carbon atom in oxygenated fuel, and it is difficult to break the bond, which restrains the formation of aromatic hydrocarbon and black carbon, so the oxygen content of ethanol can provide oxygen atom in the fuel-rich region and inhibit the formation of smoke, especially at heavy load. At heavy load, the excess air ratio is low, so the oxygen content of ethanol can show greatly positive effect on the smoke emission. On the other hand, ethanol has lower carbon and sulfur percentage, little aromatic hydrocarbon, and lower surface tension and boiling point, which can promote the spray and combustion characteristics of ethanol-diesel blends and restrain the smoke emission.

4. Conclusions

(1) The power performance of engine fueled with ethanol-diesel blends can meet the demand of prototype after adjusting the fuel delivery. With increasing atmospheric pressure, the equivalent specific fuel consumption of both mixtures and pure diesel showed the same trend of decrease. When the atmospheric pressure is lower than 90 kPa, the equivalent specific fuel consumption is significantly improved with the rise of atmospheric pressure; and the improvement is weakened when atmospheric pressure is above 90 kPa.

(2) At 81 kPa, the HC emission rises greatly with the decrease of speed and load and the increase of ethanol content, especially at low load. The increasing mix proportion of ethanol has little influence on the HC emission when atmospheric pressure ranges from 90 kPa to 100 kPa.

(3) At 81 kPa, the CO emission rises greatly with the decrease of speed and the increase of ethanol content, especially at low load. At 90 kPa and 100 kPa, the CO emission increases slightly with the increasing mix proportion at low and middle load, while the CO emission is reduced at heavy load.

(4) Atmospheric pressure and mix proportion have no obvious influence on NOx emission. Under most working conditions, NOx emission of ethanol-diesel blends has a slight drop compared to that of diesel.

(5) The smoke emission drops obviously with increasing atmospheric pressure. Furthermore, the higher mix proportion of ethanol results in the lower smoke emission. Atmospheric pressure has significant effect on the smoke emission when it is lower than 90 kPa. The influence is weakened when it is above 90 kPa.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant no. 50766001).

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