sustainability

MDPI

Article

Study on the Influence of EGR on the Combustion Performance of Biofuel Diesel at Different Ambient Simulated Pressures

Zefei Tan [1,*], Jun Wang [1], Wengang Chen [1], Lizhong Shen [2] and Yuhua Bi [2]

1 School of Mechanical and Transportation, Southwest Forestry University, Kunming 650224, China; wangjun999@swfu.edu.cn (J.W.); chenwengang999@swfu.edu.cn (W.C.)
2 Yunnan Province Key Laboratory of Internal Combustion Engines, Kunming University of Science and Technology, Kunming 650500, China; lzshen@foxmail.com (L.S.); yuhuabi97@sina.com (Y.B.)
* Correspondence: tanzefei999@swfu.edu.cn

Abstract: In order to explore the influence of EGR at different altitudes on the performance of biofuel diesel engines, a comparative experimental study is conducted with the biodiesel–ethanol–diesel B15E5 (biodiesel with 15% volume fraction, ethanol with 5% volume fraction and diesel with 80% volume fraction) mixed fuel at different EGR rate and different atmospheric pressure. The experimental results show that diesel engine power performance and economy goes up with the increase of atmospheric pressure, and it decreases with the increase of EGR rate. At 2200 rpm, the improvement range of medium and high diesel engine load is 1.5–6.8%, and that of 1800 rpm is 2.8–11.7%. At the same atmospheric pressure, with the increase of EGR rate, the power and economy turn worse. The peak combustion pressure and heat release rate both increased with the increase of the atmospheric pressure at full load. At the same atmospheric pressure, peak combustion pressure and peak heat release rate fall with the increase of EGR rate. At part load, firstly, smoke emissions fall with the increase of the load and then rise. As the atmospheric pressure goes up, the smoke emissions show a downward trend, with a decline of 6.6–40%, while the NOx emissions show a rising trend, with an increase of 1.2–8.5%. At the same atmospheric pressure, the smoke emission increase with the increase of EGR rate by 9–12.5%, and the NOx emissions increase with the decrease of EGR rate by 2.5–6.8%. The HC and CO Emissions decrease with the increase of atmospheric pressure. HC emission decreases by 9.3–19.1%, and CO emission decreases by 2.9–16.6%. At the same atmospheric pressure, the HC emission decreases with the increase of the EGR rate by 3.3–4.5% at medium and high loads, and the CO emission increases with the EGR rate by 3.1–4.5%.

Keywords: diesel engine; exhaust gas recirculation; attitude; performance; emissions

check for updates

Citation: Tan, Z.; Wang, J.; Chen, W.; Shen, L.; Bi, Y. Study on the Influence of EGR on the Combustion Performance of Biofuel Diesel at Different Ambient Simulated Pressures. *Sustainability* **2021**, *13*, 7862. https://doi.org/10.3390/su13147862

Academic Editors: Gholamhassan Najafi and Shiva Gorjian

Received: 8 June 2021
Accepted: 6 July 2021
Published: 14 July 2021

1. Introduction

With the rapid development of economy, the consumption of oil has increased dramatically, and the environmental problems are worsening day by day. The world is facing increasingly severe environmental pressure and energy security problems. Therefore, it is an urgent task to find a green alternative fuel with abundant resources and economic feasibility [1–3]. Biodiesel and ethanol have become popular biofuel alternative energy sources due to their wide range of sources, renewable and excellent performance, biodegradability, and help to alleviate the effects of greenhouse effect and haze [4,5].

Researches show that biodiesel and ethanol fuel, which are oxygenated fuel, on the one hand, can improve the combustion process of engine, and thus improve engine performance and reduce the emission of particulate matter (PM), carbon monoxide (CO), and hydrocarbon compounds (HC), especially in the plateau area [6,7]; on the other hand, the increase of oxygen content will lead to the increase of nitrogen oxide (NOx) emissions [8,9]. Asadi et al. [10] investigated the behavior of ethanol and biodiesel, blended with diesel fuel in a multiple injection engine. Their results showed that unlike biodiesel combustion, ethanol combustion resulted in lower chamber temperature and lower NOx emission subsequently. Kim et al. [11] conducted a detailed experiments on the combustion and exhaust characteristics of ethanol–diesel blended fuels with a four-stroke four-cylinder common-rail direct injection diesel engine at 750 rpm at a low speed idle, and a 40 Nm engine load. The test fuels were four types of ethanol-blended fuel. The ethanol blending ratios were 0% (DE_0) for pure diesel, and 3% (DE_3), 5% (DE_5), and 10% (DE_10) for 3%, 5%, and 10% ethanol mixtures (by vol.%), respectively. Blending ethanol with diesel fuel increased the maximum combustion pressure by up to 4.1% compared with that of pure diesel fuel, and the maximum heat release rate increased by 13.5%. The brake specific fuel consumption (BSFC) increased, up to 5.9%, as the ethanol blending ratio increased, while the brake thermal efficiency (BTE) for diesel–ethanol blended fuels remained low. When ethanol blending was applied, nitrogen oxides (NOx) reduced to 93.5% of the level of pure diesel fuel, the soot opacity decreased from 5.3% to 3% at DE_0, and carbon monoxide increased (CO) by 27.4% at DE_10 compared with DE_0. The presence of hydrocarbon (HC) decreased to 50% of the level of pure diesel fuel, but increased with a further increase in the ethanol blending ratio. Geng et al. [12] investigated the combustion and emission performance of biodiesel–diesel–ethanol fuel blends on a turbocharged diesel engine at a constant speed of 1600 rpm and seven engine loads. The results showed that the maximum cylinder pressure and the maximum heat release rates of the diesel–diesel–ethanol blends are lower than that of diesel fuel. With the increase of ethanol mixing ratio, the NOx emission of biodiesel–diesel–ethanol blends increased slightly, while the soot and CO emission decreased significantly. The HC emission of biodiesel–diesel–ethanol blends increased slightly but was still lower than the HC emission level of diesel. Liu et al. [13] studied the influence of the biodiesel–ethanol–diesel (abbreviated as BED) oxygenated fuel on the particulate matter (PM) and nitrogen oxides (NOx) emissions of a diesel engine at different altitude levels. Experimental investigations of PM and NOx emissions were performed on a high pressure common rail diesel engine fueled with pure diesel and BED oxygenated fuels at different atmospheric pressures of 81 kPa and 100 kPa. The experimental results showed that the PM and NOx emissions presented an obvious trade-off trend at different atmospheric pressures using the pure diesel fuel and the BED oxygenated fuels. At high atmospheric pressure, the drop of PM emissions and the growth of NOx emissions with the rising load both increased. Hosseinzadeh-Bandbafha et al. [14] analyzed a heavy-duty tractor diesel engine operating on diesel–biodiesel–bioethanol blends using exergetic, economic, and environmental life cycle assessment analyses. Diesel was mixed with biodiesel and bioethanol with volumetric ratios of 5–15% and 2–6%, respectively. Their results presented that in general, increasing biodiesel concentration in the fuel blend could improve the exergetic, economic, and environmental indicators of the system. However, there was no clear pattern of the effects of bioethanol on the investigated indicators. Interestingly, most of the prepared fuel blends were exergetically, economically, and environmentally superior to diesel. Overall, substituting a portion of diesel with biodiesel and bioethanol was proved to be an attractive strategy from the exergetic, economic, and environmental perspectives. Liu et al. [15] investigated the influence of different categories of oxygenated biofuels on the performance and emissions of a diesel engine in a high-altitude anoxic condition. Their test results showed that when fueled with the E10 (containing 10% ethanol in volume percentage and 90% petroleum diesel in the blend fuel) and B10E10 (containing 10% biodiesel, 10% ethanol, and 80% petroleum diesel) oxygenated blended biofuels respectively, the power performance of the diesel engine decreased. Further, the brake specific energy consumptions (BSEC) of the bended fuels were basically lower than those of the diesel fuel, and the fuel economy improved. When fueled with the B10E10 blends, the carbon monoxide (CO) emissions and the hydrocarbon (HC) emissions of the engine tended to be the pure diesel fuel level at low loads and decreased at high loads. The nitrogen oxides (NOx) emissions decreased at low loads and increased at high loads. The soot emissions of the engine with the E10 and B10E10 fuels both decreased. The hydrocarbon (HC) emissions, the soot emissions, and the carbon monoxide (CO) emissions at low loads of the diesel engine fueled with the B10E10 fuel were all lower than those of the E10 fuel, while the nitrogen oxide (NOx) emissions were basically higher than the E10 fuel level. Bi et al. [16] studied the effect of variable nozzle turbocharger (VNT) and EGR on performance of diesel engine fueled with oxygenated fuel (biodiesel-ethanol-diesel), under different atmospheric pressures. The results showed that the power and economy of the oxygenated fuel diesel engine become worse with the increase of the VNT opening and the EGR rate and the decrease of the atmospheric pressure. When the atmospheric pressure increases from 80 to 100 kPa, the average increase of NOx emissions is 11%. When atmospheric pressure decreases from 100 to 80 kPa, the average increase of smoke is 96.6%.

Currently, exhaust gas recirculation (EGR) technology is considered to be one of the most effective technical measures to reduce NOx emissions [17]. Xiao et al. [18] studied the effects of EGR rate on combustion and emission characteristics of blends of ethanol and biodiesel. Their found that EGR can significantly reduce NOx emissions from diesel engine fueled with ethanol biodiesel blends. Liang et al. [19] carried out an experimental study on the performance of engine fueled with ethanol–biodiesel using EGR. Their results showed that as ethanol concentrations in blends increase, the fuel consumption by volume increases, and HC and CO emissions increase. The use of EGR can significantly reduce NOx emissions. Tan et al. [20] studied the influences of performance of burning biomass fuel B25E5 (biodiesel with 25% volume fraction, ethanol with 5% volume fraction, and diesel with 70% volume fraction) and exhaust gas recirculation (EGR) system under plateau environment. Their experimental results showed that while burning pure diesel, the power performance with the increase of EGR rate lowered under the working conditions of external characteristic. Compared with the pure diesel fuel, when burning the B25E5 fuel, the dynamic performance felled slightly and the specific fuel consumption rose. In addition, after using EGR, the economy of the diesel engine became worse.

The previous studies on the combustion performance of biofuel diesel were usually carried out in plain areas. There are few reports about the performance and emissions of diesel engine fueled with biodiesel ethanol diesel blends in plateau areas, especially when combined with EGR. As the altitude increases, the atmospheric pressure decreases and the oxygen content in the air decreases. The oxygen content of biodiesel and ethanol is higher than that of pure diesel. The use of a mixture of biodiesel and ethanol can help alleviate the deterioration of diesel engine combustion in high altitude areas. However, the increase in the oxygen content of the fuel may lead to the formation of NOx during the combustion process. Therefore, this paper studied the effects of different EGR rates on the power performance, economy, combustion and emission characteristics of a high pressure common-rail diesel engine fueled with biodiesel–ethanol–diesel (BED) mixture at different altitudes, and analyzed the relationship between the working characteristics of the high pressure common-rail diesel engine fueled with biofuel fuel under different atmospheric pressures and its influence, which provides a theoretical basis for the application of BED biofuel fuel in plateau area.

2. Experimental Equipment and Methods

The test engine is YN30 high pressure common rail diesel engine produced by Kunming Yunnei Power Co., Ltd. (Kunming, China). The technical parameters are shown in Table 1. The main test equipments are: WE31N hydrodynamic dynamometer, FCM transient fuel consumption measuring instrument, AVL415S smoke meter, MEXA–7500DEGR exhaust gas analyser, IncaCOM electronic control calibration system, multi-channel high-performance engine transient characteristic combustion analyser, CEM101 computerized internal combustion engine atmospheric simulation integrated measurement and control system. The CEM101 device mainly consists of a dynamometer, an inlet and exhaust simulating device, a controller, and several sensors of pressure, temperature, and air flow rate. When the simulated atmospheric pressure is higher than the local atmospheric pressure, the method of pressurizing the intake and exhaust is adopted. When the simulated atmospheric pressure is 100 kPa, that is, the altitude is about 0 m, CEM101 device is used to pressurize the inlet of the diesel engine, so that the inlet pressure of the diesel engine is stabilized at 100 kPa. At the same time, the exhaust back pressure valve is adjusted to make the exhaust pressure also stable at 100 kPa. The altitude of the test place is 1912 m, and the atmospheric pressure is 81 kPa. The ambient temperature there is about 25 °C, and the relative moisture is 20–35%. Main characteristics of measurement instrumentations are presented in Table 2. The schematic diagram of measurement system is shown in Figure 1.

Table 1. Engine specifications.

Parameter Description	Details
Engine type	Four-stroke, in-line four cylinders, direct injection
Air intake system	Turbocharged, inter-cooled
Bore × Stroke	95 mm × 105 mm
Displacement	2.98 L
Compression ratio	18:1
Rated power	81 kW at 3200 rpm
Peak torque	360 N·m at 1800 rpm
Injection system	Bosch common-rail system CRS2–16

Table 2. Main characteristics of measurement instrumentation.

Instrument	Measured Quantity	Range	Accuracy
WE31N hydrodynamic dynamometer	Engine torque	0–400 N·m	±0.2%·full scale
Magnetic induction speed transducer	Engine speed	0–7500 rpm	±5 r/min
FCMA fuel consumption instrument	Fuel consumption	0–40 kg/h	<±0.05%·full scale
LFE300 air flow meter	Air volume flow rate	0–800 m^3/h	±1.0%·measure value
MEXA−7500DEGR	NOx	0–10,000 ppm	20 ppm
MEXA−7500DEGR	HC	0–50,000 ppm	10 ppm
MEXA−7500DEGR	CO	0–5000 ppm	5 ppm
AVL 415S	smoke	0–10 FSN	±0.001 FSN
AVL GH13P	Cylinder pressure	0–250 bar	<±0.5%·full scale

The composition of the B15E5 fuel blend contains 0# diesel oil (according to Chinese standards, 0# diesel oil means the diesel oil with a freezing point at 0 °C), 99.5% ethanol, biodiesel (made from waste cooking oil). The densities of biodiesel and ethanol were measured by a precision densitometer. The cetane number, lower heating value and oxygen content in weight of the B15E5 were calculated according to the corresponding formula [16]. The physical and chemical properties of the blended fuel B15E5 are shown in Table 3. Throughout the whole experimental process, there is no engine modification and atmospheric correction on the test data. Under the same measurement conditions, three measurements were used for each data collection. The average of three measurements was used to represent the test result. The uncertainty evaluation of the measured data is based on the "GUM" (Guide to the expression of Uncertainty in Measurement) method. In this paper, combined standard uncertainties of the engine brake torque, BSFC, cylinder pressure, smoke, NOx, HC, and CO emission are within 2.8 N·m, 2.98 g/(kW·h), 0.168 MPa, 0.092 FSN, 9.3 ppm, 14.3 ppm, and 4.2 ppm, respectively.

Table 3. Main physicochemical properties of fuels.

Fuel	Density (20 °C)/(g/cm^3)	Cetane Number	Lower Heating Value (MJ/kg)	Oxygen Content in Weight (%)
diesel	0.838	53.1	42.85	0.0
biodiesel	0.880	56.0	39.50	10.0
alcohol	0.789	8.00	26.78	34.8
B15E15	0.837	51.3	41.80	3.20

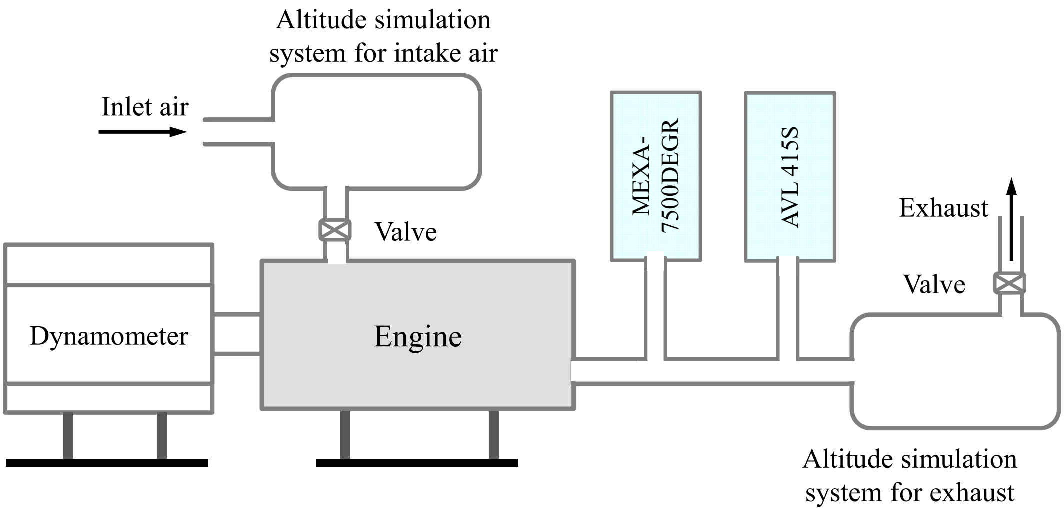

Figure 1. Schematic Diagram of the measurement system.

3. Results and Discussions

3.1. Engine Performance

Figures 2 and 3 are the respective comparison diagrams of the engine torque of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rates and atmospheric pressure of 100 kPa and 81 kPa. The test results show that with the increase of atmospheric pressure, the dynamic property increases. At 2200 rpm the average increase is 4.53%, and that is 4.02% while at 1800 rpm. When the atmospheric pressure is the same, with the increase of EGR rate, the dynamics of B15E5 fuel decreases by 8.35% and 8.22% while at 2200 rpm and 1800 rpm, respectively.

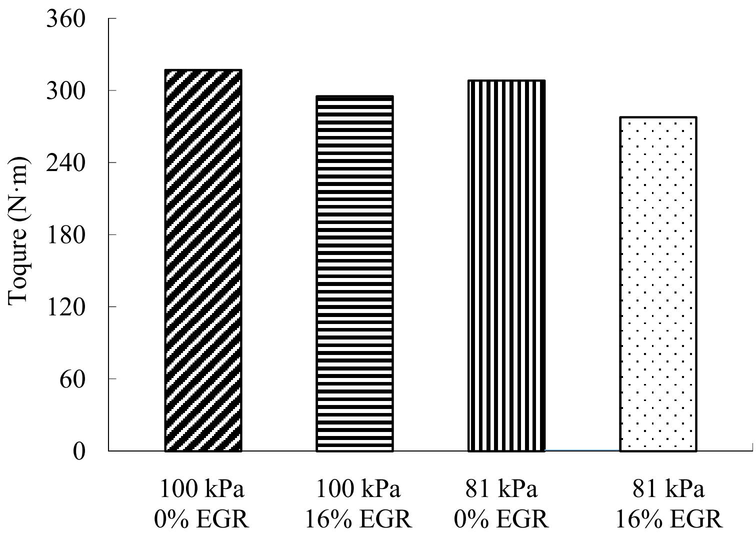

Figure 2. Torque comparison of different atmospheric pressure under 2200 rpm.

When the atmospheric pressure rises from 81 kPa to 100 kPa, the inlet air mass flow rate decreases and the combustion process deteriorates; therefore, the engine torque is reduced [21,22]. When the atmospheric pressure is the same, with the increase of EGR rate, the oxygen concentration in-cylinder and the air-to-fuel ratio decrease gradually, which leads to worse combustion quality and power performance.

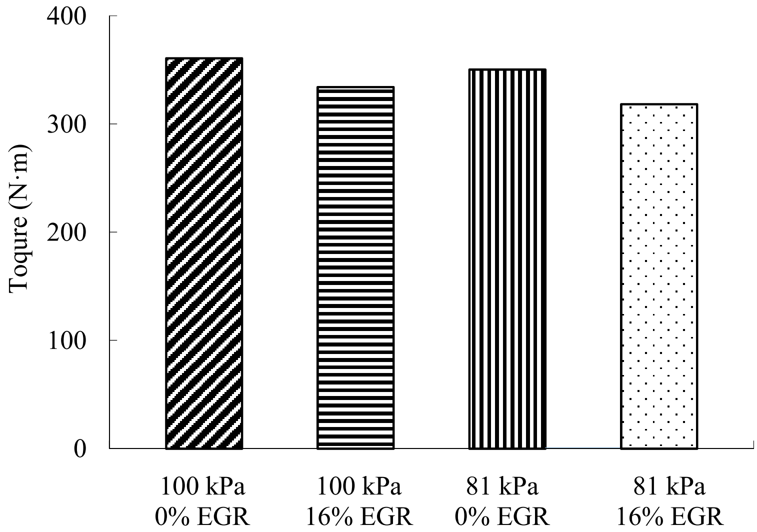

Figure 3. Torque comparison of different atmospheric pressure under 1800 rpm.

3.2. Economy

Engine economical comparison curves of load characteristics of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rates at atmospheric pressure of 100 kPa and 81 kPa are shown in Figures 4 and 5, respectively. At low load, the effective fuel consumption rate of BED fuel combustion is higher, and with the increase of load, the effective fuel consumption rate decreases gradually.

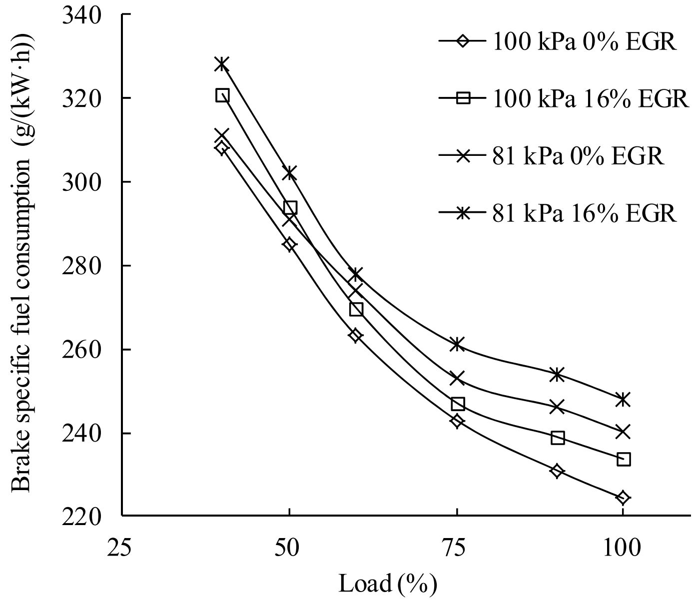

Figure 4. Economy comparison of different atmospheric pressures under 2200 rpm.

Compared with the dynamics performance at different altitudes, when the atmospheric pressure rises from 81 kPa to 100 kPa, the effective fuel consumption rate of B15E5 fuel decreases slightly at low load, but the decrease is more obvious at medium and high load areas. The decrease range of medium and high load is 1.5–6.8% at 2200 rpm, and that of 1800 rpm is 2.8–11.7%. When the atmospheric pressure is the same, the EGR rate has little effect on the effective fuel consumption rate at small load, but at medium and high load, the effective fuel consumption rate increases with the increase of EGR rate. Compared with 0% EGR, the effective fuel consumption rate of B15E5 fuel at 16% EGR increases slightly when the engine speeds are at 2200 rpm and 1800 rpm.

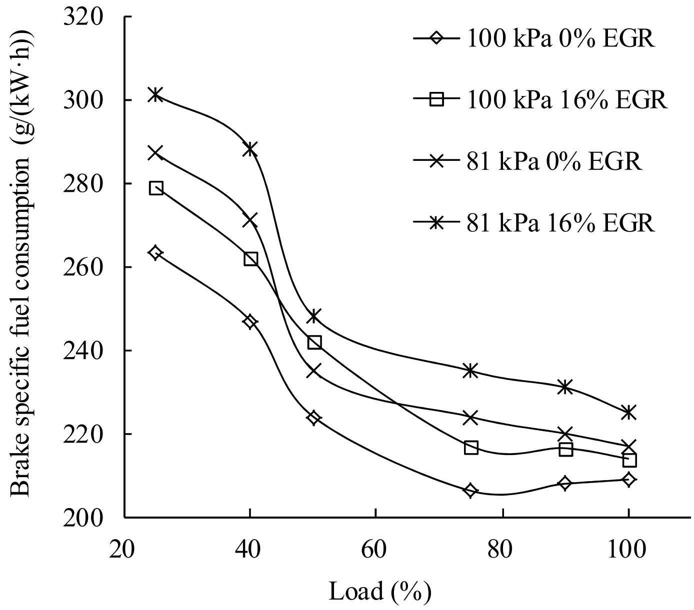

Figure 5. Economy comparison of different atmospheric pressures under 1800 rpm.

When the load is small, the fuel cannot combust completely at low temperature, which leads to increase of the fuel consumption [23]. As the load increases, the temperature rises and the combustion is improved. When the atmospheric pressure rises, with the increase of the air density the intake air mass flow rate increases. In addition, the combustion process and the fuel consumption improve with the help of oxygen content of biodiesel and ethanol, which improves the incomplete combustion of the rich mixture. At the same atmospheric pressure and the small load, because the fuel supply is small and the excess air coefficient is large, the EGR rate has little effect on the fuel economy. At medium and high loads, with the increase of the EGR rate, the excess air ratio and the combustion rate decreases; moreover, polyatomic molecular gases such as CO_2 and H_2O in the exhaust gas increase, which causes the decrease of specific heat capacity of the mixture and the temperature in-cylinder, and results in poor fuel economy. A small EGR rate should be used at big load [24,25] in order to avoid excessive economical degradation of the engine.

3.3. Cylinder Pressure and Heat Release Rate

Figures 6 and 7 are the cylinder pressure curves of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rates and the atmospheric pressure of 100 kPa and 81 kPa respectively. It can be seen that when the atmospheric pressure is the same, the maximum cylinder pressure of 16% EGR at 2200 rpm and 1800 rpm are both lower than the maximum cylinder pressure at 0% EGR. The maximum combustion pressure of the diesel engine decreases with the increase of EGR rate. When the atmospheric pressure is different, the maximum cylinder pressure increases while the atmospheric pressure changes from 81 kPa to 100 kPa.

When the atmospheric pressure is the same, the increase of EGR rate leads to the decrease of the excess air coefficient and the quantity of combustible mixture, which results in the reduction of the maximum cylinder pressure [26,27]. When the atmospheric pressure increases, with the increase of the inlet gas pressure and the air oxygen content, it is favorable to form the combustible mixture so as to raise the maximum cylinder pressure.

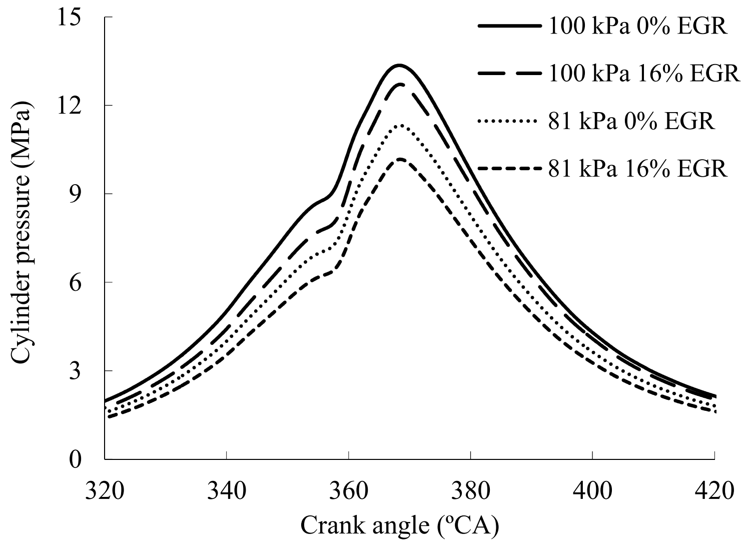

Figure 6. Cylinder pressure comparison of external characteristic under 2200 rpm.

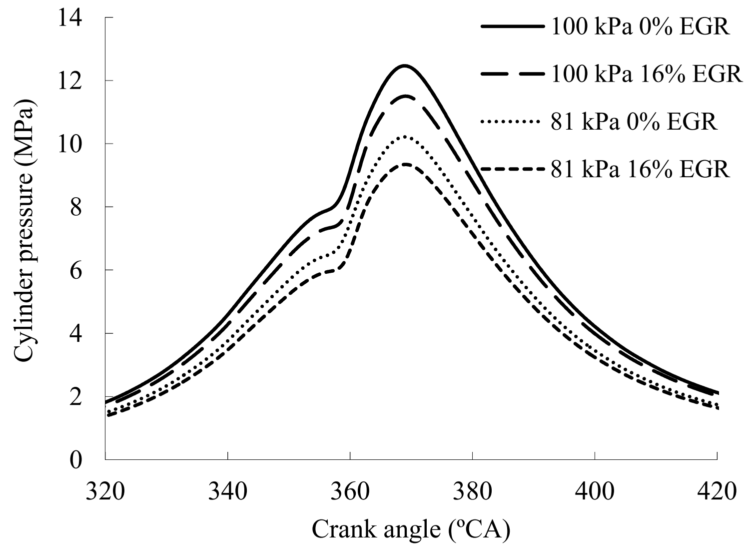

Figure 7. Cylinder pressure comparison of external characteristic under 1800 rpm.

The comparison of the heat release rates of B15E5 fuel at 2200 rpm and 1800 rpm at different EGR rates and the atmospheric pressures of 81 kPa and 100 kPa are shown in Figures 8 and 9, respectively, which shows that the peak heat release rate at 100 kPa is higher than that of 81 kPa, and when the atmospheric pressure is the same, the peak heat release rate of 0% EGR is higher than that of 16% EGR.

When the atmospheric pressure increases, with the increase of the inlet gas pressure and excess air coefficient, the combustion becomes more sufficient, and accordingly the peak heat release rate increases. When the atmospheric pressure is the same, with the increase of EGR rate, the combustible mixture is diluted and the ignition delay period is prolonged, which causes the decrease of the oxygen concentration, so the oxygen concentration in-cylinder decreases. Thus, the combustion process is delayed and combustion efficiency becomes worse, which leads to incomplete combustion and the decrease of the peak heat release rate [28].

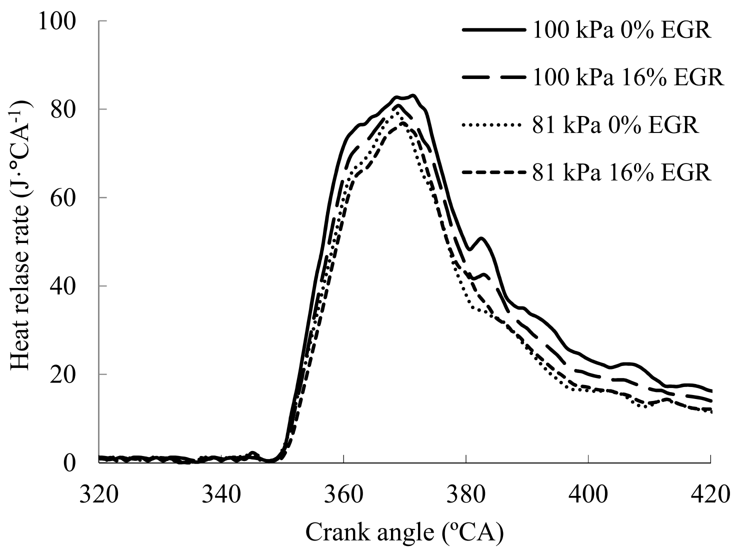

Figure 8. Heat release rate comparison of external characteristic under 2200 rpm.

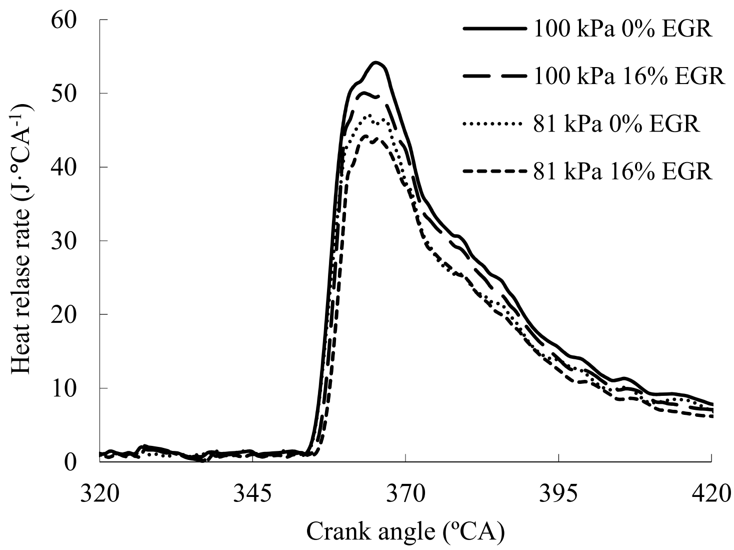

Figure 9. Heat release rate comparison of external characteristic under 1800 rpm.

3.4. Smoke and NOx Emission

Figures 10 and 11 show respectively the comparison of smoke emission of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rates and the atmospheric pressure of 81 kPa and 100 kPa. It can be seen from the figures that as the load increases, the smoke emission first decreases and then increases. When the atmospheric pressure rises from 81 kPa to 100 kPa, the smoke emission slightly decreases. Compared with 81 kPa at 2200 rpm, the smoke emission at 100 kPa drop is 6.6–40%; at 1800 rpm, the smoke emission at 100 kPa drop is 15–25%. When the atmospheric pressure is the same, the EGR rate has no obvious effect on smoke emission in the middle and low load area. In the high load area, the smoke emission shows an upward trend with the increase of EGR and the increase range is 9.0–12.5%.

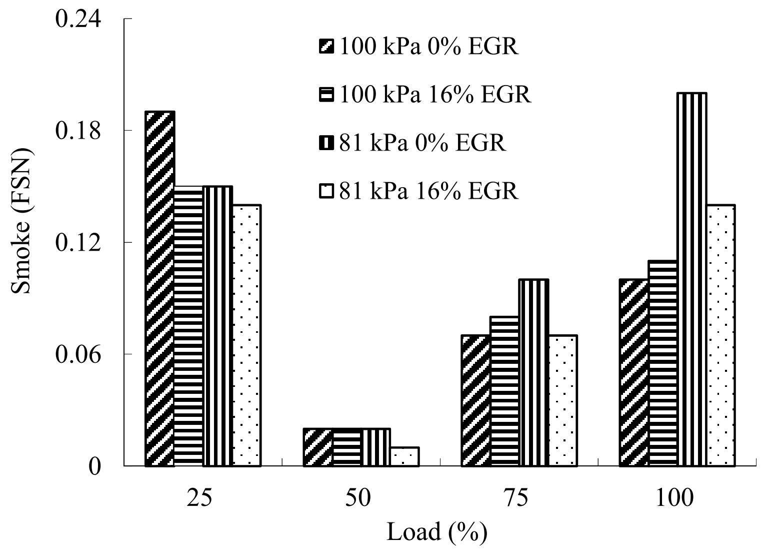

Figure 10. Smoke emission comparison of different atmospheric pressure under 2200 rpm.

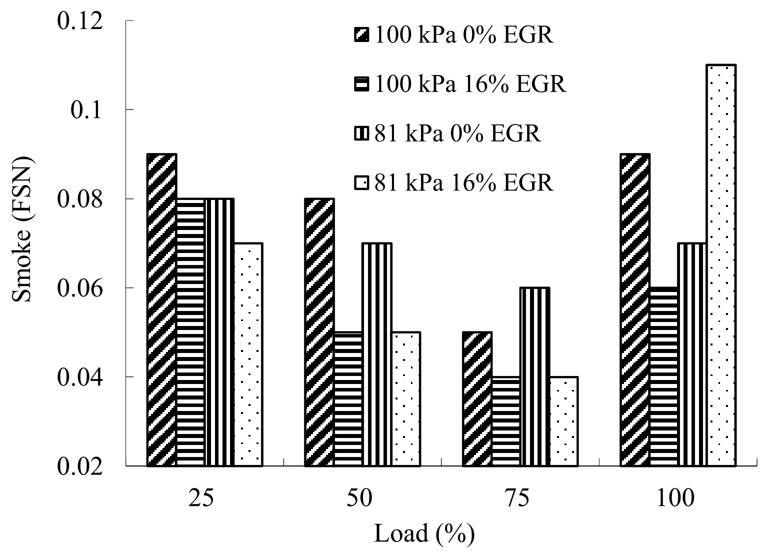

Figure 11. Smoke emission comparison of different atmospheric pressure under 1800 rpm.

When the load is low, the low temperature in-cylinder leads to insufficient combustion, and the smoke emission is high. With the increase of the load, the temperature in-cylinder turns high, and the combustion process is improved; therefore, the smoke emission is reduced. At the high load, with the increase of the fuel injection quantity, the excess air coefficient turns small, so the combustion is insufficient, which leads to high amount of smoke emission. When the atmospheric pressure rises from 81 kPa to 100 kPa, the intake air mass flow rate increases, so the air-to-fuel ratio increases, which improves the combustion process and the smoke emission. At the same atmospheric pressure, with the increase of EGR rate, more residual exhaust gas enters the engine cylinder and the fresh air volume decreases, which results in the reduction of excess air coefficient [29] and the smoke emission increases.

The NOx emission comparison of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rates and the atmospheric pressures of 81 kPa and 100 kPa are shown in Figures 12 and 13, respectively. It can be seen that with the increase of the atmospheric pressure, the NOx emission shows an upward trend, and the amplitude NOx emission is 1.2–8.5% at 2200 rpm, and 2.3–6.2% at 1800 rpm when the atmospheric pressure goes up from 81 kPa to 100 kPa. When the atmospheric pressure is the same, the EGR rate has no obvious effect on

NOx emission in the low load region, while at medium and high loads, the NOx emission decreases with the increase of the EGR rate. Compared with the no EGR, NOx emission reduces from 2.5% to 6.8% at 16% EGR rate.

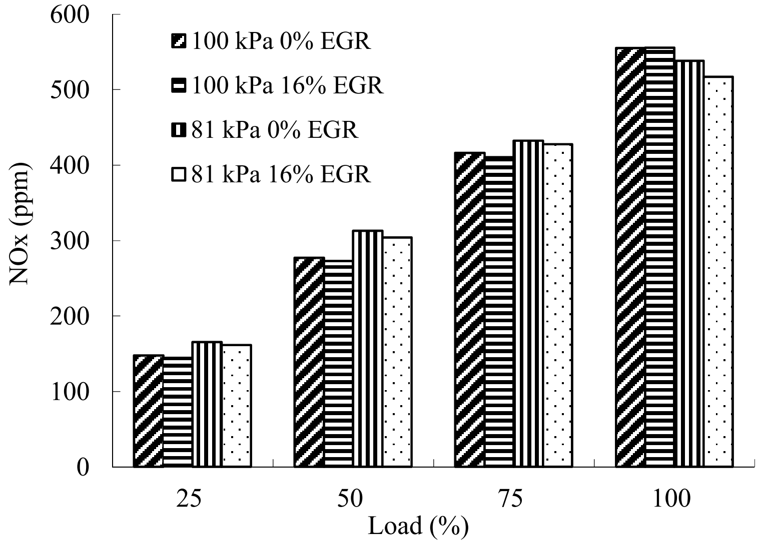

Figure 12. NOx emission comparison of different atmospheric pressure under 2200 rpm.

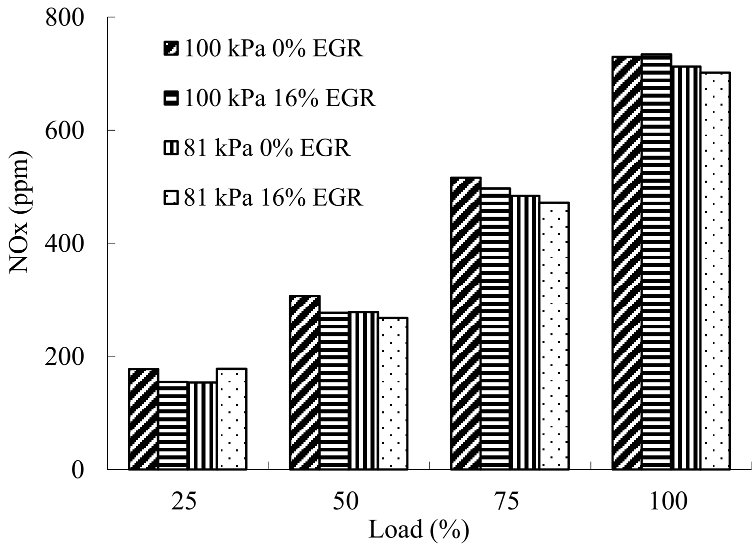

Figure 13. NOx emission comparison of different atmospheric pressure under 1800 rpm.

When the atmospheric pressure goes up, the increase of oxygen content in-cylinder is favorable to the formation of NOx. When the atmospheric pressure is 81 kPa, the reduction of the oxygen content in-cylinder inhibits the formation of NOx [17]. At low load, temperature has a greater impact on NOx formation; at medium and low loads, temperature is considered to have a greater impact on NOx formation than oxygen; at high loads, oxygen is considered to have a greater impact on NOx formation than temperature. At certain atmospheric pressure, EGR has a weak influence on excess air coefficient at low load; however, EGR reduces the combustion temperature in the cylinder and at the same time reduces the oxygen concentration in the intake gas at medium and high load, thus reducing the NOx emissions [30].

3.5. HC and CO Emission

Figures 14 and 15 show the comparison of HC emissions of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rate and atmospheric pressures of 81 kPa and 100 kPa, respectively. When the engine speed is 2200 rpm, and the load is under 60%, HC emission decreases with the increase of load. When the load is between 60% and 80%, HC emission increases with the rise of load. When the engine speed is 1800 rpm, HC emission decreases with the increase of load, and the change is more obvious at low load, but less at high load. When the atmospheric pressure is rises from 81 kPa to 100 kPa, the HC emission decreases, and the decrease range is 9.3–19.1%; when the atmospheric pressure is the same, at the medium and high load area, the HC emission shows a downward trend with the increase of EGR rate and the decrease range is 3.3–4.5%.

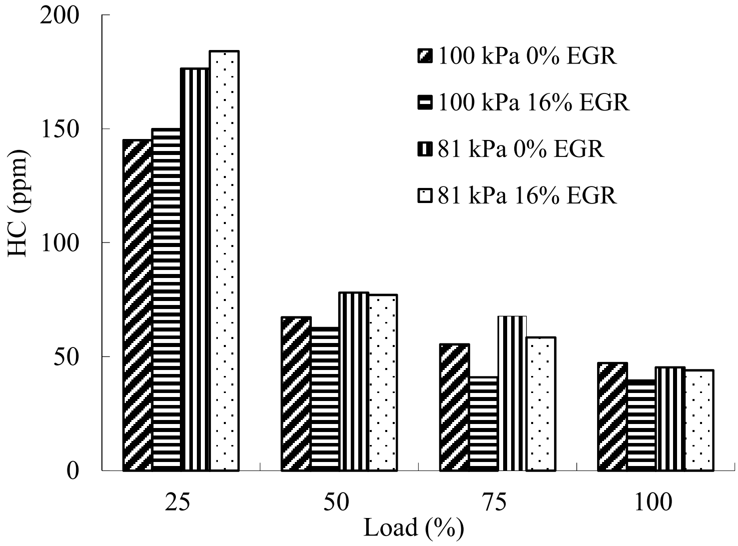

Figure 14. HC emission comparison of different atmospheric pressure under 2200 rpm.

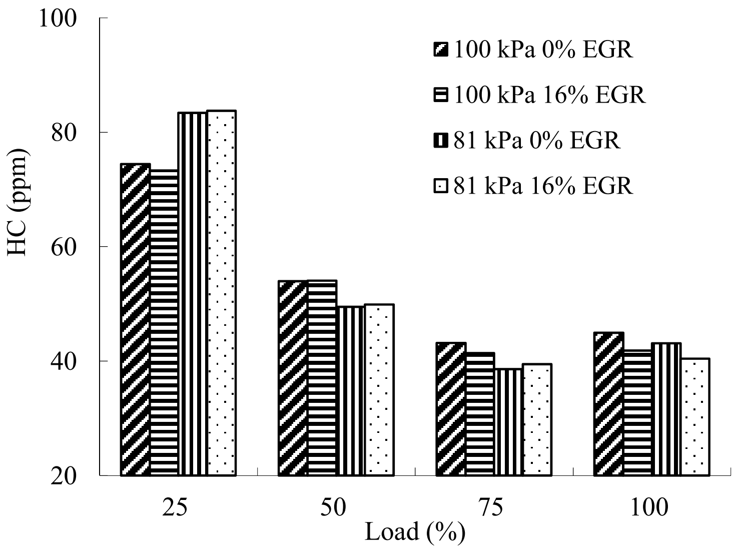

Figure 15. HC emission comparison of different atmospheric pressure under 1800 rpm.

The analysis concluded that when the load is 40% at 2200 rpm, the in-cylinder combustion temperature is low, which is not conducive to the ignition process and HC oxidation. As the load increases, with the increase of the amount of combustible mixture, the retardation period shortens, so the combustion temperature gradually increases, and HC emissions decrease. In the middle load area, with the increase of load, with the increase of the combustion speed, the in-cylinder combustion of diesel engine is insufficient, and the HC concentration is also higher in exhaust gas; in the high load area, because the combustion temperature is very high, and the self-oxygen supply of B15E5 fuel is obvious, so the ignition delay period is shortened, which leads to the reduction of HC emission. At low load of 1800 rpm, low combustion temperature leads to more thin mixture in the ignition delay period. With the increase of load, the in-cylinder temperature gradually increases, and HC emission decreases significantly. When the atmospheric pressure rises, the intake air is better and the combustion is more sufficient, so HC emission is lower; when the atmospheric pressure is the same, with the increases of EGR rate, the greater the exhaust gas recirculation rate is, the more obvious the effect of heating the intake air is, and the shorter the ignition delay period [30,31], which is beneficial to improve HC emission.

The CO emission comparison of B15E5 fuel at 2200 rpm and 1800 rpm under different EGR rates and the atmospheric pressures of 81 kPa and 100 kPa are shown in Figures 16 and 17, respectively. The main reason for CO formation is the incomplete combustion of hydrocarbon fuel. In addition, the local high temperature thermal decomposition is also an important reason for CO formation during the combustion process. It can be seen from the figures that when the atmospheric pressure rises from 81 kPa to 100 kPa, the CO emission decreases and its decreasing amplitude is 2.9–16.6%. When the atmospheric pressure is the same, as the EGR rate increases, the CO emission shows an upward trend, with an increase of 3.1–4.5%.

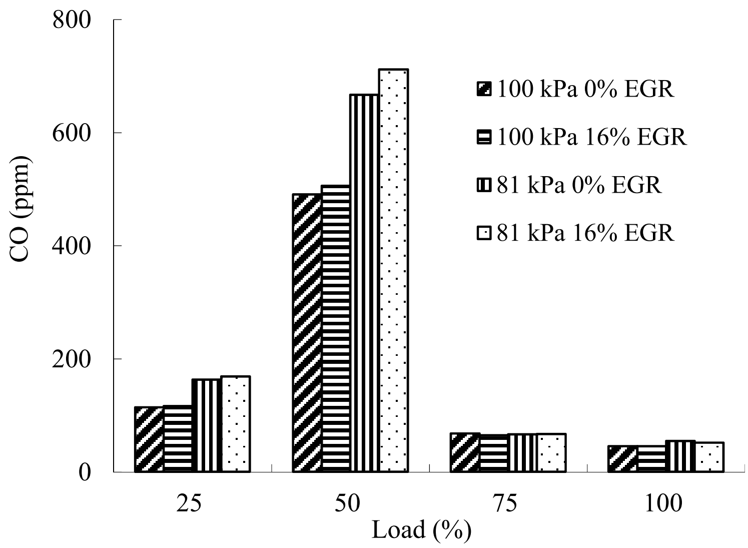

Figure 16. CO emission comparison of different atmospheric pressure under 2200 rpm.

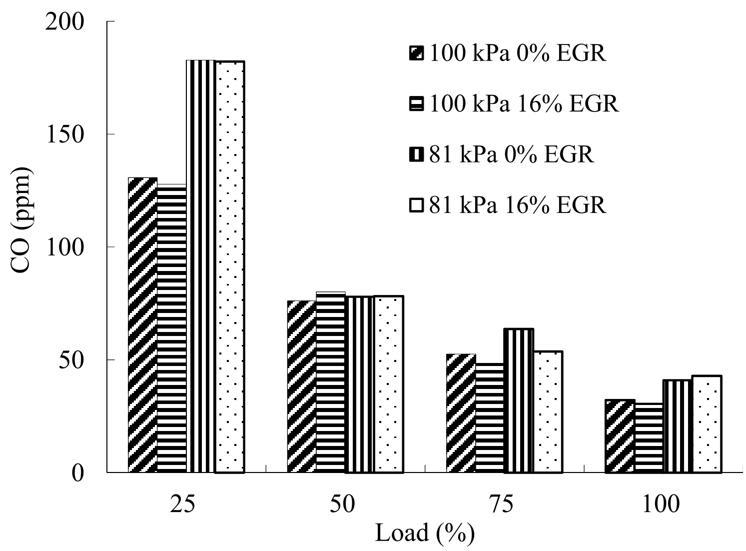

Figure 17. CO emission comparison of different atmospheric pressure under 1800 rpm.

When the atmospheric pressure rises, the air intake condition is better and the combustion is more sufficient, so the CO emission is much lower. At the same pressure, the in-cylinder oxygen concentration decreases with the increase of the EGR rate, and combustion temperature in-cylinder also decreases, so the CO concentration in exhaust gas also increases.

4. Conclusions

Through the experiments, after the study and the analysis of the effects of combustion of B15E5 fuel on the performance of high pressure common-rail diesel engine under different atmospheric pressures under different EGR rates, three conclusions can be drawn as follows.

(1) As the atmospheric pressure increases, the diesel engine power performance of B15E5 fuel increases. At the same atmospheric pressure, the power performance deteriorates with the increase of EGR rate. With the increase of atmospheric pressure, the brake specific fuel consumption shows a downward trend and its decreasing amplitude is 1.5–11.7%. At the same atmospheric pressure, the brake specific fuel consumption increases with the increase of EGR rate and the diesel engine economy turns worse.

(2) Under the external characteristic conditions, with the increase of atmospheric pressure, the maximum cylinder pressure and peak heat release rate both increase; at the same atmospheric pressure, the maximum cylinder pressure and peak heat release rate of the diesel engine both decrease with the increase of EGR rate, and their location of crank angle is slightly delayed.

(3) At partial load conditions, with the increase of load, the smoke emission decreased first and then increased. With the increase of atmospheric pressure, decrease of the smoke emission ranges from 6.6% to 40%, but the increase of NOx emission ranges from 1.2% to 8.5%; however, the emission of HC and CO decreases from 9.3% to 19.1% and from 2.9% to 16.6%, respectively. Both HC and CO emissions show a downward trend.

Finally, it should be noted that only some operating points were selected to study the effect of EGR on the performance and emissions of burning biofuels in this study, and the altitude is only 0 m and 1912 m. In the subsequent research process, more operating points and more altitude conditions will be considered. In addition, the impact on the performance of diesel engines fueled by biodiesel–ethanol–diesel mixed fuel is manifold. EGR is only one of the more important factors. In the future, the effects of injection timing, injection pressure and pre-injection parameters on the performance and emissions of diesel engine fueled with biodiesel ethanol diesel blends will be further studied, and the combustion process in cylinder will be simulated by computational fluid dynamics.

Author Contributions: Conceptualization, Z.T. and L.S.; methodology, Z.T.; formal analysis, W.C.; investigation, W.C.; resources, L.S. and Y.B.; data curation, J.W.; writing—original draft preparation, Z.T.; writing—review and editing, J.W.; visualization, W.C.; supervision, Y.B.; project administration, L.S.; funding acquisition, L.S and Y.B. All authors have read and agreed to the published version of the manuscript.

Funding: The authors receive no financial support for the research, authorship and/or publication of this article.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the need for further research.

Acknowledgments: The authors would like to acknowledge Zhong Wu engineer of Kunming Yunnei Power Co., Ltd. for his technical support in this research.

Conflicts of Interest: The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

1. Jiang, D.; Huang, Z. *Internal Combustion Engine Alternative Fuel Combustion*; Xi'an Jiaotong University Press: Xi'an, China, 2007.
2. Lin, C.Y.; Li, R.J. Engine performance and emission characteristics of marine fish-oil biodiesel produced from the discarded parts of marine fish. *Fuel Process. Technol.* **2009**, *90*, 883–888. [CrossRef]
3. Yilmaz, N. Performance and emission characteristics of a diesel engine fuelled with biodiesel–ethanol and biodiesel–methanol blends at elevated air temperatures. *Fuel* **2012**, *94*, 440–443. [CrossRef]
4. De Caro, P.S.; Mouloungui, Z.; Vaitilingom, G.; Berge, J.C. Interest of combining an additive with diesel–ethanol blends for use in diesel engines. *Fuel* **2001**, *80*, 565–574. [CrossRef]
5. Shi, X.; Yu, Y.; He, H.; Shuai, S.; Wang, J.; Li, R. Emission characteristics using methyl soyate–ethanol–diesel fuel blends on a diesel engine. *Fuel* **2005**, *84*, 1543–1549. [CrossRef]
6. Huang, Z.H.; Lu, H.B.; Jiang, D.M.; Zeng, K.; Liu, B.; Zhang, J.Q.; Wang, X.B. Study on combustion characteristics of a DI diesel engine operating on diesel/methanol blends. *Trans. CSICE* **2003**, *21*, 401–410.
7. Sendzikiene, E.; Makareviciene, V.; Janulis, P. Influence of fuel oxygen content on diesel engine exhaust emissions. *Renew. Energy* **2006**, *31*, 2505–2512. [CrossRef]
8. Boldaji, M.T.; Ebrahimzadeh, R.; Kheiralipour, K.; Borghei, A.M. Effect of some BED blends on the equivalence ratio, exhaust oxygen fraction and water and oil temperature of a diesel engine. *Biomass Bioenergy* **2011**, *35*, 4099–4106. [CrossRef]
9. Chen, H.; Wang, J.; Shuai, S.; Chen, W. Study of oxygenated biomass fuel blends on a diesel engine. *Fuel* **2008**, *87*, 3462–3468. [CrossRef]
10. Asadi, A.; Kadijani, O.N.; Doranehgard, M.H.; Bozorg, M.V.; Xiong, Q.; Shadloo, M.S.; Li, L.K. Numerical study on the application of biodiesel and bioethanol in a multiple injection diesel engine. *Renew. Energy* **2020**, *150*, 1019–1029. [CrossRef]
11. Kim, H.Y.; Ge, J.C.; Choi, N.J. Effects of Ethanol–Diesel on the Combustion and Emissions from a Diesel Engine at a Low Idle Speed. *Appl. Sci.* **2020**, *10*, 4153. [CrossRef]
12. Geng, L.M.; Cheng, Q.B.; Chen, Y.; Wei, Y.T. Combustion and emission characteristics of biodiesel-diesel-ethanol fuel blends. *China J. Highw. Transp.* **2018**, *31*, 236–242.
13. Liu, S.; Shen, L.; Bi, Y.; Lei, J. Effect of BED oxygenated fuel on the PM and NOx emissions of a diesel engine at different altitude levels. *Acta Sci. Circumstantiae* **2018**, *38*, 1791–1796.
14. Hosseinzadeh-Bandbafha, H.; Rafiee, S.; Mohammadi, P.; Ghobadian, B.; Lam, S.S.; Tabatabaei, M.; Aghbashlo, M. Exergetic, economic, and environmental life cycle assessment analyses of a heavy-duty tractor diesel engine fueled with diesel–biodiesel-bioethanol blends. *Energy Convers. Manag.* **2021**, *241*, 114300. [CrossRef]
15. Liu, S.H.; Shen, L.Z.; Bi, Y.H.; Zhang, S.B. Effects of biomass on performance and emissions of diesel engine high-altitude hypoxic condition. *Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 53–59.
16. Bi, Y.; Tang, C.; Shen, L.; Wen, W.; Wang, J.; Song, G. Effect of VNT and EGR coupling on performance of diesel engine fueled with oxygenated fuel under different atmospheric pressures. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 38–45.
17. Wang, B.; Yan, W.S.; Shen, J.W.; Chen, H.; Ye, M. Effect of biodiesel/diesel blend fuel on combustion and emission characteristic of common rail diesel engine under different atmospheric pressures. *Trans. CSICE* **2013**, *34*, 58–63.
18. Huang, H.; Li, Z.; Teng, W.; Huang, R.; Liu, Q.; Wang, Y. Effects of EGR rate on combustion and emission characteristics of blends of ethanol and biodiesel. *J. Combust. Sci. Technol.* **2019**, *25*, 237–243.
19. Liang, Y.; Zhou, L.; Yao, G.; Ding, X.; Zhou, J.; You, S. Experiment study on performance of engine fueled with ethanol-biodiesel using EGR. *Renew. Energy Resour.* **2015**, *33*, 1736–1742.
20. Tan, Z.F.; Bi, Y.H.; Di, Y.L.; Ouyang, W.B.; Shen, L.Z. Effects of EGR system under plateau environments on performance of diesel engine used biomass materials fuels. *J. Cent. South Univ. For. Technol.* **2015**, *33*, 109–113.
21. Liu, S.; Shen, L.; Zhang, S. A research on the stability of BED blend fuel and its effects on the engine performance in plateau area. *Automot. Eng.* **2012**, *34*, 816–820.
22. Zheng, W.; Hu, D.Z.; Wen, L.Q.; Yao, X.G.; Shen, Y.G.; Shen, L.Z. Effects of EGR on the economic performance and smoke intensity of diesel engines working at different altitude. *Small Intern. Combust. Engine Motorcycle* **2006**, *35*, 9–12.
23. Cai, M.; Yang, X.; Sun, P. Study on the combustion process and emission of a turbocharged diesel engine with EGR. *Small Intern. Combust. Engine Motorcycle* **2008**, *37*, 68–71.
24. Hu, Z.L.; Bian, Q.; Gao, B.; Gao, W.Z. Internal EGR technology and its Application in the diesel engine for small excavator. *Small Intern. Combust. Engine Motorcycle* **2013**, *42*, 1–4.
25. Wang, Y.; Dong, R. Investigation of EGR system in MD&HD CR diesel engine. *Chin. Intern. Combust. Engine Eng.* **2011**, *32*, 6–11.
26. Peng, H.; Cui, Y.; Shi, L.; Deng, K. Effects of EGR on combustion process of DI diesel engine during cold start. *Trans. CSICE* **2007**, *25*, 193–201. [CrossRef]
27. Bai, C.X.; Liu, Z.C.; Han, Y.Q.; Li, K.; Liu, J.W. Effect of Stepped EGR on combustion process of a heavy-duty diesel engine. *Trans. CSICE* **2011**, *29*, 8–15.
28. Shen, L.Z.; Bi, Y.H.; Zhang, W.; Lei, J.L.; Yan, W.S.; Yang, Y.Z.; Zhang, N. Combustion process of turbocharged and inter-cooled turbocharged diesel engine in different altitude regions. *J. Combust. Sci. Technol.* **2005**, *11*, 524–529.

29. Du, D.; Gu, J. Study of the influence of EGR on soot formation in diffusion flames. *J. Combust. Sci. Technol.* **2002**, *8*, 529–532.
30. Chen, S.H.; Wang, Z.; Yuan, Y.N.; Wang, L.; Zhang, X.C. The effect of EGR on cycle to cycle variation and combustion process of diesel engine. *Automot. Eng.* **2006**, *28*, 343–345.
31. Jia, H.; Liu, S.; Yin, B.; Huang, C. Visualization of influence of EGR on combustion process and emission performance for light-duty diesel engine. *Trans. Chin. Soc. Agric. Eng.* **2012**, *28*, 44–49.