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Experimental Study of Injection Parameters on the Performance of a Diesel Engine with Fischer–Tropsch Fuel Synthesized from Coal

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Abstract: Experimental research was conducted on a turbo-charged, inter-cooling and common-rail diesel engine with Fischer–Tropsch fuel synthesized from Coal-to-liquid (CTL), in order to investigate the influence of different injection parameters on the combustion, emissions and efficiency characteristics of the engine. The results showed that the ignition point was advanced, the in-cylinder pressure and heat release rate increased as the injection timing advanced and the injection pressure increased. By comparing the peak in-cylinder pressure of 100 cycles for one sample, it was found that the coefficient variation (*COV*) remained under 2% throughout the tests and the combustion process remained stable. NO_x emissions decreased with delayed injection timing and lower injection pressure. In contrast to NO_x emissions, soot emissions were almost zero when the injection pressure was up to 143.5 MPa. The indicated thermal efficiency (ITE) showed no obvious change with different injection parameters, and remained under 40% in all the tests.

Keywords: energy; engine; injection parameters; combustion; emissions; efficiency

1. Introduction

As one of the most important power sources of automobiles, diesel engines have played an irreplaceable role in the transportation industries due to their high thermal efficiency and good reliability. However, the level of soot emissions and NO_x emissions restricts the application prospects of diesel engines due to increasingly stricter emissions regulations and the strong demand for green travel. Researchers worldwide have made efforts to achieve progress not only in the field of diesel emission control via catalytic filters [1,2], but also in the field of alternative fuel for diesel engines [3–8]. Di Sarli et al. investigated the effect of highly-dispersed ceria nanoparticles on diesel particulate filters [1] and performed CFD-based simulation of soot combustion dynamics in a catalytic diesel particulate filter [2]. Yatish et al. used the Taguchi method to improve the emissions and researched the optimization of emissions from diesel engines [9–11]. Coal-to-liquid (CTL) is a subsidiary product of the coal chemical industry that has been demonstrated to be a promising clean alternative fuel to diesel. With recent improvements in the preparation techniques, the high quality of CTL can be guaranteed and its specifications even exceed commercial diesel [12–14]. Moreover, CTL is low cost compared to diesel and has been used in many countries where the coal resources are abundant [15–17]. Therefore, in-depth research on CTL is necessary to develop its potential as an alternative fuel to improve the performance of automobile engines.

Compared with traditional fossil fuels, CTL has numerous advantages, which have been extensively researched since 1935 [18]. Kim et al. analyzed the production of Fischer–Tropsch CTL fuel and its potential as an alternative automotive fuel [19]. Song et al. discussed the potential of CTL for reducing exhaust emissions in the European steady state cycle (ESC) test mode [20]. The results indicated that the emissions decreased compared with diesel fuel, while there was no obvious difference in the total particle number. Zuo et al. investigated the combustion and vibration performance of a turbocharged engine operated with diesel blended with methanol [21]. They found that when the engine was fueled with CTL, the ignition delay became shorter, in-cylinder pressure decreased slightly and the combustion process became smoother compared with 0# diesel. Liu et al. compared the combustion characteristics in a Euro III diesel engine with Fischer-Tropsch (F-T) fuel and diesel fuel [22]. The results showed that the peak in-cylinder pressure rise rate of CTL was significantly higher than that of diesel fuel. Moreover, the indicated thermal efficiency (ITE) of the engine increased by 4.5% on average. Hao et al. studied the emissions of carbonyl compounds (CBCs) in a light-duty diesel engine fueled with CTL [23]. The total CBCs, formaldehyde and acetaldehyde were reduced when CTL was used. Huang et al. investigated the influence of different delivery advance angles on engine performance in an unmodified single-cylinder, direct-injection, diesel engine fueled with F-T fuel [24]. They found that the proportion of pre-combustion to diffusion combustion decreased and combustion duration slightly increased when the engine was fueled with F-T diesel compared with 0# diesel. When the delivery advance angle was pushed back by 3 °CA, NO_x emissions greatly decreased. Gill introduced the physicochemical properties of CTL and analyzed its application prospects as an alternative fuel [15].

Compared with 0# diesel, the combustion and emissions of CTL show different characteristics with different injection parameters. Research into CTL alternative fuel is essential, and can address the problems of both environmental protection and energy resources. However, previous research has mainly concentrated on the pure engine performance, and there are scarce reports about the effects of the injection parameters on combustion stability, the combustion process, emissions and the efficiency characteristics of a diesel engine fueled with CTL. The performance advantages of CTL have not yet been fully studied and highlighted. An electronically-controlled diesel engine has the advantage of adjustable parameters and a quick response time. When the injection parameters and fuel are not a reasonable match, the engine performance cannot be the best. This study aims to investigate the effects of injection parameters on the performance and emissions characteristics of a four-cylinder diesel engine, in order to promote combustion, reduce emissions and improve the efficiency of the engine.

2. Materials and Methods

2.1. Research Engine Test Bench

In this research, a turbo-charged, inter-cooling, in-line, four-cylinder, common-rail diesel engine was used. The main specifications of the engine are shown in Table 1. An electrical eddy current dynamometer of 160 kW was matched with the engine, which was used to control the engine speed and torque. The fuel supply system was a common rail system produced by Bosch Company (Stugart, Germany). The injection pressure and injection timing of the common rail system were adjusted using a MCV100 system (V1, Kunming University of Science and Technology, Kunming, China), which can manage fuel delivery according to the engine operation condition. The fuel consumption was measured using an intelligent oil consumption meter. The setup of the test bench is shown in Figure 1.

The exhaust emissions were measured using an AVL 483 smoke meter (V1, AVL, Graz, Austria) and SESAM i60 system (V1, AVL, Graz, Austria). A piezo-electric type pressure sensor (6058A, Kistler, Winterthur, Switzerland) was used to measure in-cylinder pressure. Under each operating condition, the combustion data was collected over 100 cycles and analyzed by a combustion analyzer system. The steady state data was collected at least twice to eliminate the effect of systematic error on test results. The accuracy and uncertainty of all key instruments are given in Table 2.

Table 1. Specifications of the test engine.

Specifications	-
Model	Electronically controlled
Type	Water-cooled, turbo-charged
Engine displacement [L]	3.298
Bore × stroke [mm × mm]	100 × 105
Fuel injection system	Common-rail fuel system
Calibration power [kW]/speed [r/min]	85/3200
Maximum torque [Nm]/speed [r/min]	315/1600–2400

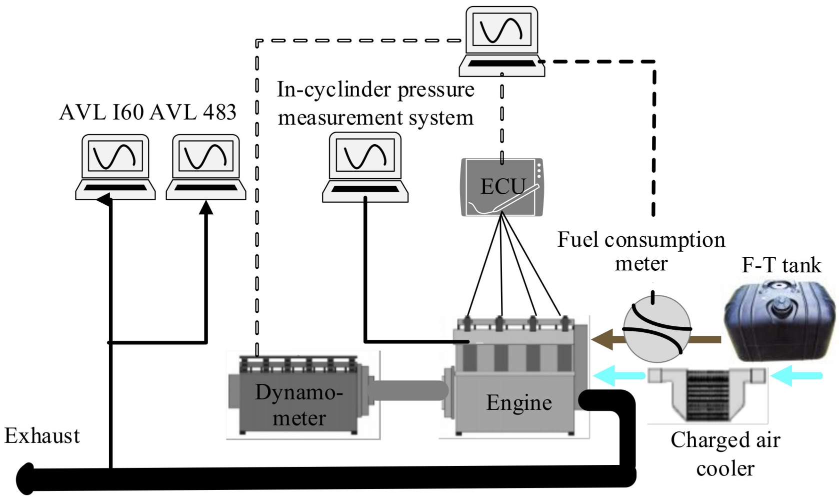


Figure 1. Test bench setup. ECU: Electronic Control Unit; F-T: Fischer-Tropsch

Table 2. Accuracy and uncertainty of the measuring equipment. F-T: Fischer-Tropsch.

Instrument	Parameters	Range	Accuracy	Uncertainty (%)
Electric eddy current	Torque	0–600 Nm	0.4%	-
Dynamometer	Speed	0–8000 r/min	0.1%	-
Fuel consumption meter	F-T Diesel	0–20 kg	0.4%	-
Emission analyzer	NO_x	0–10,000 ppm	20 ppm	2.8
Smoke meter	SOOT	0–50 mg/m^3	0.001 mg/m^3	0.3
Pressure sensor	In-cylinder pressure	0–250 MPa	0.05 MPa	0.3

2.2. Test Fuel

The main specifications of the CTL fuel and China VI (It indicates the oil grade) diesel used in this study are shown in Table 3 Compared with the China VI diesel, the CTL had the properties of no sulfur content, lower aromatic content, density, boiling point temperature, higher heating value and cetane value (CN) number.

Table 3. The main specifications of the fuel.

Specifications	0#-Diesel	F-T-Diesel
Density at 20 °C [g/cm^3]	0.81	0.76
Initial boiling point [°C]	200	180.5
End boiling point [°C]	375	311.5
Sulfur content [mg/kg]	10	0
Aromatic content [%]	≤7	0.009
Heating value [J/k]	42,652	47,128
CN	55.8	62.5

2.3. Test Conditions

During the entire experiment, the engine was operated at the maximum torque speed of 2000 r/min with a 50% load. The inlet air was kept at 45–55 °C by the inter-cooling system and the engine cooling water temperature was controlled in the range of 75–85 °C by the external water circulating system throughout the test. The engine was warmed up before the test to keep it in the same state. In order to enhance the comparability of the results, one injection parameter was changed in each condition. The tests were strictly implemented according to the predetermined procedures. The obtained test data were complete and clear and the results showed good repeatability.

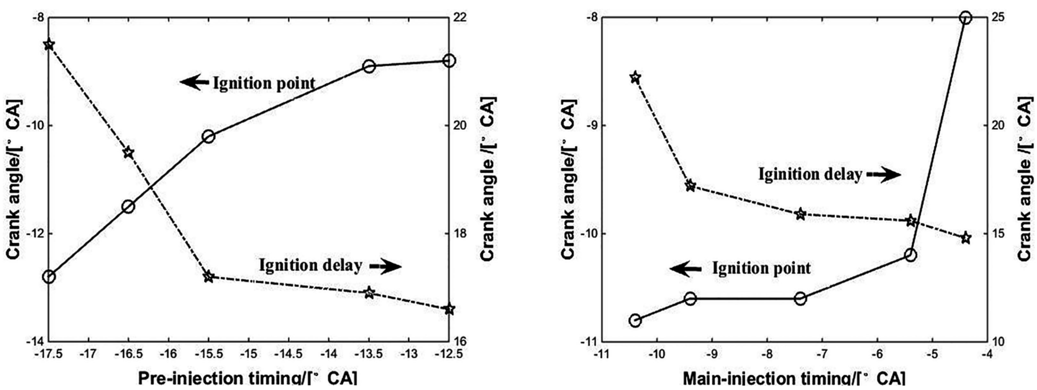
3. Results

3.1. Combustion Process Analysis

The combustion process includes a series of complex physical and chemical reactions, which directly determines the thermodynamic state of the cylinder and is very important for the engine performance. The influence of the injection parameters on the ignition point and ignition delay is shown in Figure 2. The ignition point is defined as the crank angle where $dQ_B/d\phi$ is zero. The ignition delay is defined as the crank angle from the ignition point to 5% of the cumulative heat release rate [25].

The influence of the fuel injection timing on the ignition point and ignition delay is shown in Figure 2a,b. It was found that the combustion started earlier and the ignition delay became longer when the injection timing was advanced. When the pre-injection timing varied from −12.5 to −17.5 °CA, the ignition point advanced as much as 4 °CA, and the ignition delay extended by 4.9 °CA. The effect of the main-injection timing on the ignition point was less than that of the pre-injection timing, but it strongly affected the ignition delay. The ignition delay increased by 7.4 °CA when the main-injection timing changed from −4.4 to −10.4 °CA. The mixing process of fuel and air increased with early injection timing and the whole combustion process was brought forward, and the ignition point appeared in advance. In general, when fuel is injected into a combustion chamber whose temperature and pressure are low, more time is needed to prepare the combustion conditions and the ignition delay period would also ultimately be extended.

The variation of the combustion process with different injection pressures is presented in Figure 2c. It was found that the combustion started a little earlier, and the ignition delay was slightly shortened with the increase in injection pressure. The atomization of fuel was improved and the fuel/air mixing process was also intensified when the injection pressure increased. The phase of evaporation, diffusion and mixing became shorter, and therefore the combustion started early. As the fuel injection pressure increased, the heat release rate curve moved forward, then the corresponding phase advanced, thus the ignition delay was reduced.



(**a**) (**b**)

Figure 2. *Cont.*

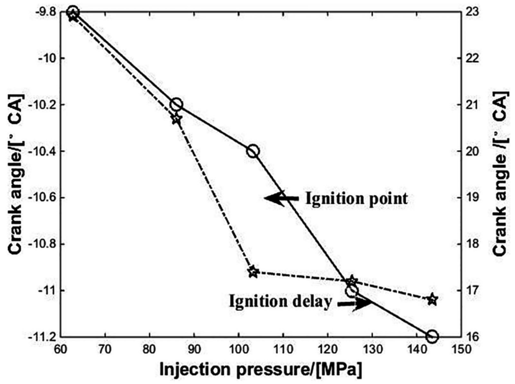


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Figure 2. Effects of different injection parameters on the combustion parameters. (**a**) Different pre-injection timings; (**b**) Different main-injection timings; (**c**) Different injection pressure.

3.2. Combustion Feature Analysis

Figure 3a,b present the variation curves of the in-cylinder pressure and heat release rate with different injection timings. It can be seen that the in-cylinder pressure and heat release rate increased with early injection timing. Due to the lower cylinder temperature and in-cylinder pressure with early injection timing, the ignition delay was prolonged. During ignition, the mixing time of the fuel and air injected into the cylinder chamber increased. It is known that when the proportion of premixed combustion increases, more and better mixture will be formed [26]. Pre-injection timing did not delay or advance the entire combustion process, thus the in-cylinder pressure and heat release rate were more sensitive to main-injection timing.

Figure 3c shows the changes in the in-cylinder pressure and heat release rate with different injection pressures. It was found that the cylinder pressure and heat release rate increased with the increase of injection pressure, which was possibly due to the fact that the atomization of fuel was improved. Moreover, the amount and the quality of mixture formed during the ignition delay period obviously increased, and thus more energy were released during the combustion process. Consequently, the combustion started earlier, and the peak in-cylinder pressure and heat release rate increased with the increase in injection pressure.

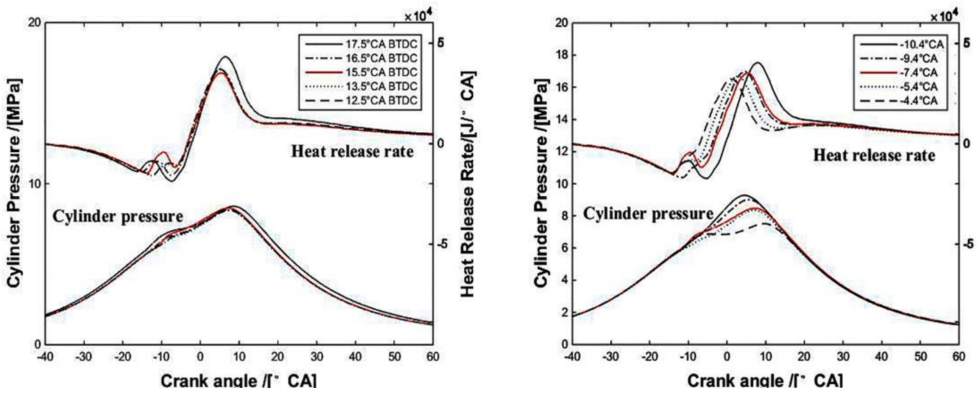

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Figure 3. *Cont.*

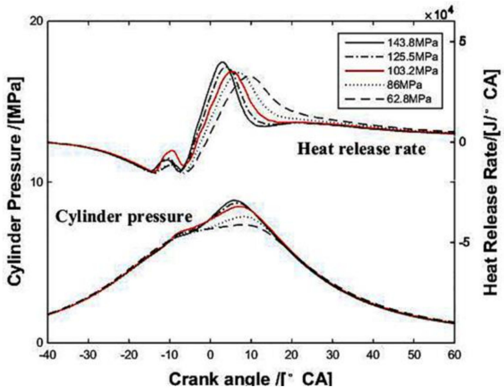

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Figure 3. Effects of different injection parameters on the combustion process. (**a**) Different pre-injection timings; (**b**) Different main-injection timings; (**c**) Different injection pressures.

3.3. Combustion Stability Analysis

The peak in-cylinder pressure of 100 cycles at different injection times and injection pressures are shown in Figure 4. It can be concluded from Figure 4a,b that the peak in-cylinder pressure was more sensitive to the change with the main-injection timing than the pre-injection timing. This was because the in-cylinder temperature and heat release rate obviously increased when the main injection timing was advanced. Thus, the in-cylinder pressure significantly increased.

The influence of the injection pressure on the peak in-cylinder pressure is shown in Figure 4c. The peak in-cylinder pressure increased as the injection pressure increased. This is attributed to the improved fuel atomization and accelerated combustion rate as the injection pressure increased.

Coefficient variation (*COV)* is the most important indicator to study the cycle-to-cycle variation of each cylinder and it is defined as below [27–29].

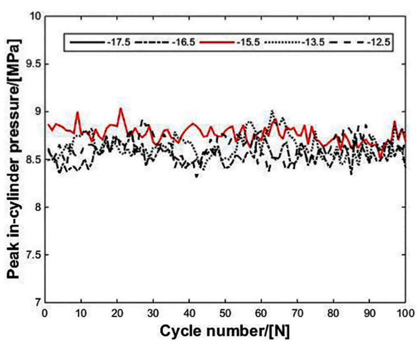
$$COV = \sigma\sqrt{x} \times 100\%, \tag{1}$$

$\overline{x}$ is the average value and σ is the standard deviation, which is defined as follows.

$$\sigma = \sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2 / (n-1)}, \tag{2}$$

where n is the total number of cycles in one sample.

The *COV* of the peak in-cylinder pressure for 100 cycles at different injection parameters is provided in Figure 5. It was found that the *COV* increased with delayed injection timing, and the level of *COV* remained almost the same at different injection pressures. The *COV* remained under 2% throughout the tests. It can be concluded that combustion was relatively stable.



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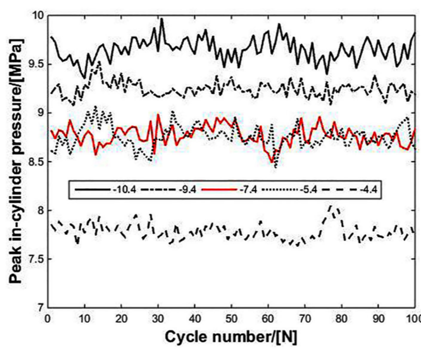

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Figure 4. *Cont.*

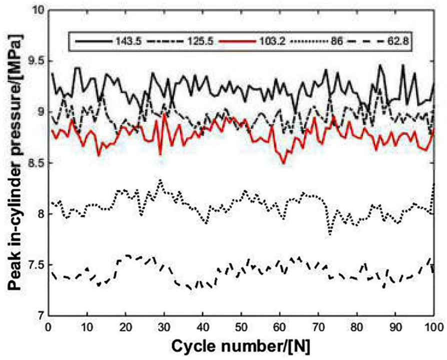

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Figure 4. Effects of different injection parameters on the combustion stability. (**a**) Different pre-injection timings; (**b**) Different main-injection timings; (c) Different injection pressure

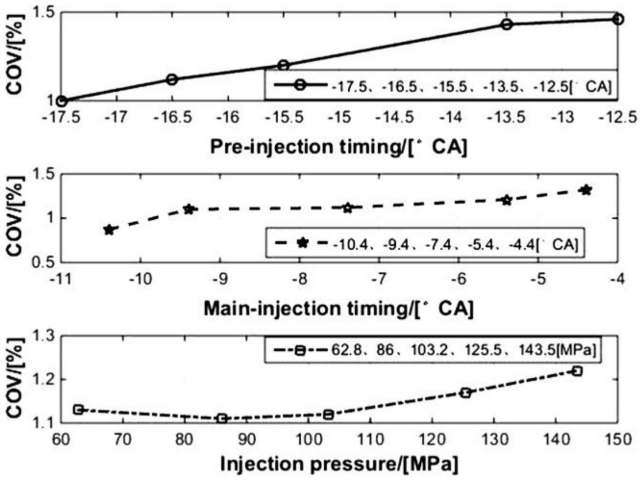

Figure 5. Effects of different injection parameters on the coefficient variation (*COV*).

3.4. Emissions Analysis

Figure 6 presents the variation of NO_x emissions with different injection parameters. It was found that NO_x emissions decreased along with the delayed injection timing and lower injection pressure. NO_x emissions reduced by 44 ppm for −17.5 °CA pre-injection timing to −12.5 °CA pre-injection timing, while NOx emissions reduced by 171 ppm for −10.4 °CA pre-injection timing to −4.4 °CA main-injection timing. When the injection pressure varied from 62.8 to 143.5 MPa, the NO_x emissions increased by 110 ppm.

Oxygen concentration, high temperature duration and combustion temperature are the main factors that strongly influenced the NO_x formation rate [30]. It was found in Section 3.2 that the heat release rate decreased with delayed injection timing. Therefore, the delayed injection timing led to the lower heat release rate and cylinder temperature, resulting in a decrease in the NO_x emissions. However, the engine power and fuel economics may become worse with delayed injection timing, which may cause the problem of hard-to-burn fuel. As the injection pressure increased, the injection duration became shorter, and the spray quality was improved. Consequently, the ratio of initial fuel amount to cycle fuel quantity increased, which then accelerated the speed of mixing and combustion. Therefore, the center of the heat release rate curve can be closer to the top-dead-center (TDC).

Figure 7 presents the variation in soot emissions with different injection parameters. It can be observed that the soot emissions decreased as the injection timing advanced. When the pre-injection timing varied from −12.5 to −17.5 °CA, the soot emissions decreased by 0.19 mg/m^3. The soot emissions reduced by 52.19% at the −10.4 °CA main-injection timing compared with −4.4 °CA main-injection timing. The soot emissions sharply decreased as the injection pressure increased, and there were almost no soot emissions when the injection pressure was up to 143.5 MPa. According to Figure 7, the capability to reduce soot emissions with different injection parameters from high to low can be sequenced as injection pressure > main-injection timing > pre-injection timing. This order is closely related to the ignition delay trend.

Soot emissions are known to be very sensitive to the ignition delay, volatility and distribution of the fuel/air mixture. The fuel/air mixing process plays a significant role in reducing soot emissions. As illustrated in Sections 3.1 and 3.2, the ignition delay increased as the injection timing advanced and the injection pressure increased. The delayed ignition delay can improve the fuel/air mixing process. Early injection timing can contribute to reducing the intensity of the diffusion combustion. However, the soot emissions mainly form in the diffusion combustion phase. When the fuel is injected into the cylinder chamber at high pressure, the capability of the volatility can be improved and too lean or too dense areas can be reduced As a result, the fuel/air mixing process can be better. Under the early injection timing and high injection pressure conditions, the longer residence of soot at high temperatures will result in less soot emissions.

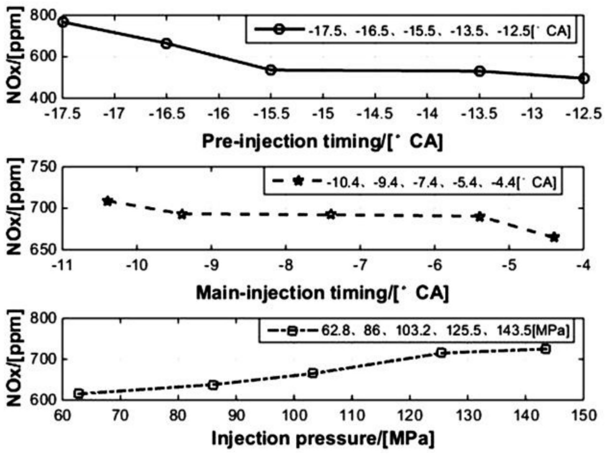

Figure 6. Effects of different injection parameters on NO_x emissions.

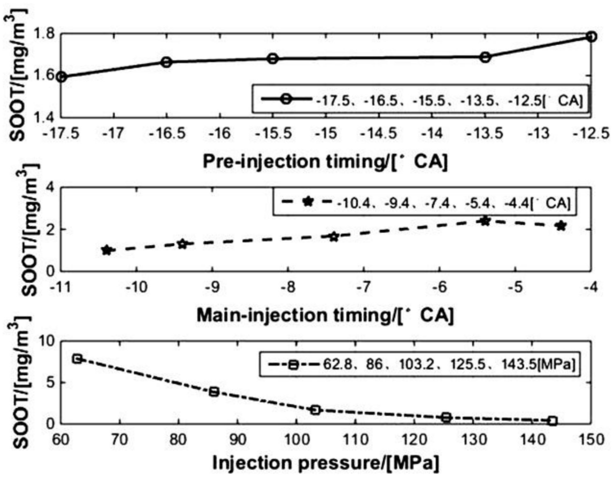

Figure 7. Effects of different injection parameters on soot emissions.

3.5. Efficiency Analysis

ITE is the ratio of the indicated power of the actual cycle to the heat of the fuel consumed, which reflects the efficiency of the thermal power conversion. It is defined as follows.

$$\eta_{it} = p_i / g_b \cdot H, \tag{3}$$

where p_i is the indicated power;.g_b is the fuel consumption per cycle for one cylinder; and kg. H is the heat of fuel, kJ/kg.

Figure 8 presents the plots of ITE versus different injection parameters. ITE can be influenced by many factors, such as the heat release rate and combustion phase, etc. It is known that the combustion phase advances with early injection timing, and the ITE increases as the combustion phase advances due to enhanced constant volume combustion near the TDC [31]. Thus, the ITE increases with early injection timing. Moreover, the ITE increases with the increase in injection pressure, because the premixed combustion ratio and heat release rate increase with the increases in injection pressure, which leads to improved constant volume combustion. The ITE remained under 40% for all the tests.

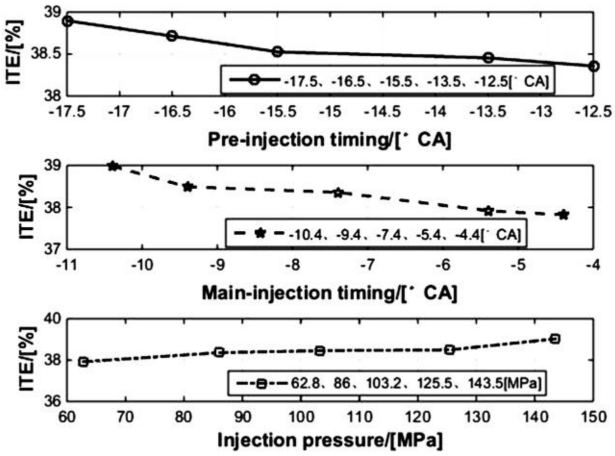

Figure 8. Effects of different injection parameters on efficiency.

4. Conclusions

The influence of the injection parameters on engine performance was investigated in a four-cylinder, common-rail, diesel engine fueled with CTL, and the following main conclusions were drawn from the results.

Injection timing and injection pressure had a significant effect on the combustion process. The whole combustion process was brought forward or pushed back with the change of the main-injection timing. When the main-injection timing changed from −4.4 °CA to −10.4 °CA, the ignition point advanced by 2.8 °CA and the ignition delay increased by 7.4 °CA. The in-cylinder pressure and heat release rate increased with earlier injection timing and higher injection pressure. Compared with pre-injection timing, the in-cylinder pressure and heat release rate were more sensitive to main-injection timing. NO_x emissions decreased with the delayed injection timing and lower injection pressure, while soot emissions decreased as the injection timing advanced and the injection pressure increased. When the main-injection timing was delayed to −10.4 °CA compared to −4.4 °CA, the NO_x emissions decreased by 171 ppm. The decrease in soot emissions was much larger than the increase in NO_x emissions caused by the increase of injection pressure. The soot emissions were almost zero when the injection pressure was up to 143.5 MPa. The ITE increased with the earlier injection timing and higher injection pressure, and it remained in the range 37.9–39.0% throughout the tests. The ITE increased with the earlier injection timing and higher injection pressure, and maintained the range of 37.9–39.0% throughout all the tests.

In summary, the order of influence of the different injection parameters on the performance of a common-rail diesel engine was revealed. It was found that the injection timing and injection pressure were the key factors affecting the engine performance. To optimize regular injection, these the two key factors should be considered as the main variables. When this engine was operated with a 2000 r/min–50% load, the best injection parameters were found to be 103.2 MPa injection pressure, 15.5 °CA BTDC pre-injection timing and 7.4 °CA BTDC main injection timing. The adaptability of CTL for electrical engines can be improved by adjusting the injection parameters when engines operate at different conditions. This study provides guidance for the combustion of CTL in electrical diesel engines with high efficiency, which is of great importance for the optimization of the injection parameters of electrical diesel engines.

Author Contributions: The contributions of the individual authors to this research are as follows: J.S. designed the test program and wrote the paper based on the experiment data, T.W. guided the paper and made many useful suggestions for its improvement. T.Y., Z.Z (Zhen Zhao) and Z.Z. (Zhengwu Zhang) performed the experiments.

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Conflicts of Interest: The authors declare no conflict of interest.

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