

Article

Combustion Study of Polyoxymethylene Dimethyl Ethers and Diesel Blend Fuels on an Optical Engine

Jingjing He ¹, Hao Chen ^{1,*}, Xin Su ¹, Bin Xie ² and Quanwei Li ¹

¹ School of Automobile, Chang'an University, Xi'an 710064, China; hejj0117@126.com (J.H.); sx1994514@126.com (X.S.); 2018222003@chd.edu.cn (Q.L.)

² Shaanxi Motor Group Co., Ltd., Xi'an 710200, China; xb13319223597@163.com

* Correspondence: colen7680@126.com or chenhao@chd.edu.cn; Tel.: +86-29-82334471

Abstract: Polyoxymethylene dimethyl ethers (PODE) are a newly appeared promising oxygenated alternative that can greatly reduce soot emissions of diesel engines. The combustion characteristics of the PODE and diesel blends (the blending ratios of PODE are 0%, 20%, 50% and 100% by volume, respectively) are investigated based on an optical engine under the injection timings of 6, 9, 12 and 15-degree crank angles before top dead center and injection pressures of 100 MPa, 120 MPa and 140 MPa in this study. The results show that both the ignition delay and combustion duration of the fuels decrease with the increasing of PODE ratio in the blends. However, in the case of the fuel supply of the optical engine being fixed, the heat release rate, cylinder pressure and temperature of the blend fuels decrease with the PODE addition due to the low lower heating value of PODE. The addition of PODE in diesel can significantly reduce the integrated natural flame luminosity and the soot formation under all injection conditions. When the proportion of the PODE addition is 50% and 100%, the chemical properties of the blends play a leading role in soot formation, while the change of the injection conditions have an inconspicuous effect on it. When the proportion of the PODE addition is 20%, the blend shows excellent characteristics in a comprehensive evaluation of combustion and soot reduction.

Keywords: polyoxymethylene dimethyl ethers; optical engine; combustion; injection strategy; flame



Citation: He, J.; Chen, H.; Su, X.; Xie, B.; Li, Q. Combustion Study of Polyoxymethylene Dimethyl Ethers and Diesel Blend Fuels on an Optical Engine. *Energies* **2021**, *14*, 4608. <https://doi.org/10.3390/en14154608>

Academic Editor:
Constantine D. Rakopoulos

Received: 23 June 2021
Accepted: 23 July 2021
Published: 29 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

As oligomers of ethers, polyoxymethylene dimethyl ethers with the structure $\text{CH}_3\text{O}-(\text{CH}_2\text{O})_n-\text{CH}_3$ (noted as PODE, “n” can take values from 1 to 8) are newly appeared promising oxygenated additives that can greatly reduce the soot emissions of diesel engines. In general, PODE is synthesized mainly by a compound that provides a terminal group at both ends (mainly including methanol, dimethyl ether, methylal, etc.) and a compound that provides an intermediate main chain $-\text{CH}_2\text{O}-$ (mainly including formaldehyde, trioxane, paraformaldehyde, etc.) under the catalysis of an acidic catalyst [1–4]. PODE can be dissolved in any proportion to diesel under normal temperature and pressure [5]. The main properties of the PODE components compared to diesel and biodiesel are shown in Figure 1 [6–13]. The boiling points of the PODE components are all lower than a 95% distillation temperature of biodiesel or diesel. The viscosity of PODE_n at 20 °C ranges from 0.58 MPa·s to 2.84 MPa·s, with n varying from 1 to 6, which is lower than that of diesel or biodiesel. A low boiling point temperature of PODE is conducive to a high volatility and excellent uniformity of the air–fuel mixture. The low viscosity of PODE may be helpful for the improvement of the spray quality. The cetane number (CN) of the PODE components increases from 63 to 104 when n varies from 2 to 6, and thereby, PODE has a higher CN than diesel, which exhibits a better ignitability [14,15]. Among the major components of PODE, PODE_2 has a low flash point and does not meet the safety standards [16]. The melting points may be too high when n is greater than 5. Therefore, PODE_{3-5} is a satisfactory additive for diesel.

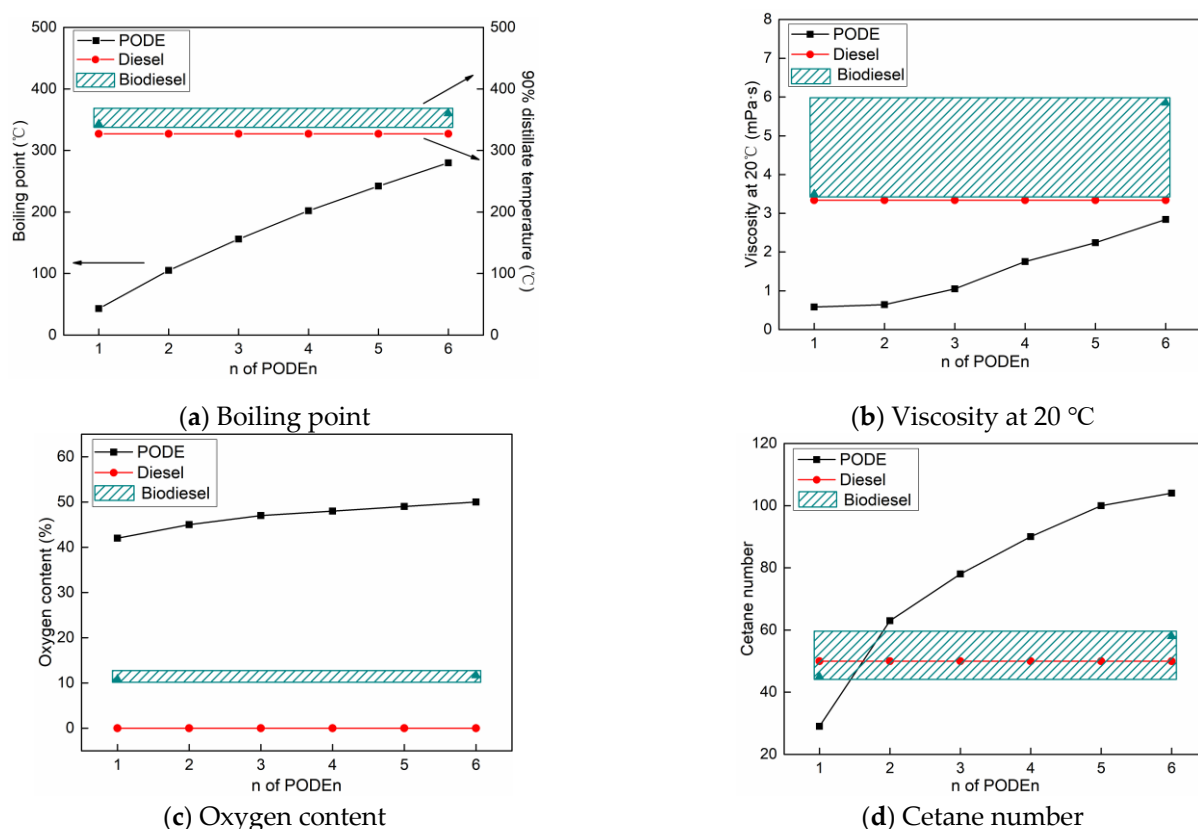


Figure 1. The main properties of PODEn, reproduced from References [6–13].

PODE as an ideal alternative fuel for diesel can effectively improve the combustion quality and reduce the diesel pollutant emissions due to the excellent proprieties. Firstly, the lower viscosity and distillation temperature of PODE than diesel helps to improve the quality of fuel spray and atomization and the uniformity of the air–fuel mixture. Secondly, PODE has a much higher oxygen content than diesel. A large number of active free radicals and oxygen atoms can be generated to promote the fuel full combustion. Thirdly, PODE have a high H/C ratio and no C–C bond, indicating a high capability to decrease the soot formation [17,18]. Research has shown that the formation of a soot precursor decreases as the oxygen content increases [19], while it increases as the C–C bond number increases [20].

Previous studies have indicated that adding PODE in diesel is a promising way to make diesel engines realize the goal of high efficiency and clean combustion. Li et al., studied the spray and atomization characteristics of PODE and diesel blends under the ambient temperature of 293 K and the ambient pressure of 4 MPa [21]. They found that the spray-projected area increased with a small amplitude and the diameter of the droplets decreased significantly with the increasing of the PODE ratio in the blends. The droplets had a trend of even distribution in the range of 12–20 μm . Therefore, blending PODE with diesel can improve the performance of spray atomization. Ma et al., investigated the flame combustion characteristics and soot distribution of PODE and diesel blend fuels in a constant-volume vessel [22]. The flame lift-off length increased and the soot amount decreased with the increasing of the PODE volume fraction in the blends. When the volume fraction of PODE reached 20% and 50%, the total soot emissions amount decreased more than 50% and 95%, respectively. For one thing, the special structure of PODE with no C–C bond can reduce the soot formation. For another, a high oxygen content can accelerate the soot oxidation [22–24]. In addition, a large number of scholars have also studied the combustion and emission characteristics of PODE and diesel blend fuels based on actual engines. The results showed that the start of combustion (SOC) advanced and, thereby, the ignition delay (ID) shortened with the PODE blending ratio [25]. The diffusion

combustion intensity was stronger and the combustion duration (CD) of the blends was shorter than the diesel fuel [17,26]. The maximum cylinder temperature and the fuel combustion speed of the main injection fuel increased, and the combustion quality of blend fuels improved obviously as the blending ratio of PODE increased in the blends under the test conditions [26]. The larger the PODE blending ratio in diesel, the greater the reduction in soot emissions of diesel engines. Liu et al., employed 10%, 20% and 30% PODE volume ratios as additive in diesel, which can reduce the soot emissions of the four-cylinder diesel engine by 27.6%, 41.5% and 47.6% [27]. Chen et al., also found that adding PODE in diesel/biodiesel mixtures can significantly reduce the soot emissions under medium and high loads and reduce the number concentrations of ultrafine particle matters under low and partial loads [13]. Liu et al., studied the influence of PODE on soot emissions in a diesel engine, and the results showed that PODE can reduce soot emissions greatly over the European Stationary Cycle [11]. Pellegrini et al., blended PODE with a 10% volume ratio in diesel and tested the blends in an old Euro-2 diesel [14]. The soot emissions of the old Euro-2 diesel car that used a PODE/diesel fuel blend reached below the Euro IV limit. By blending 25% PODE by volume into commercial diesel, the raw soot emissions of heavy-duty diesel engines can be reduced by 73–94%, which met the Euro VI soot emission standard in the World Harmonized Stationary Cycle [9]. Wang et al., used PODE₃₋₄ as a diesel additive to improve the combustion and emission characteristics of a diesel engine. The results revealed that adding a 20% PODE₃₋₄ volume ratio in diesel reduced the soot emissions by 36.2% compared to pure diesel in the European Stationary Cycle [24]. In all, PODE can effectively reduce soot emissions due to its excellent properties and special chemical structure. However, PODE has a lower heating value (LHV) of 25.81 MJ/kg, whereas the LHV of diesel is 44.94 MJ/kg. A high ratio of PODE in blends affects the power performance of the diesel engine [27]. The break-specific fuel consumption increased with the increasing of the PODE blending ratio [28]. Liu et al., found that the BTE of the diesel engine first increased and then decreased with the increasing of the PODE blending ratio [25]. The BTE of diesel, P10, P20 and P30, are 40.3%, 42.5%, 43.7% and 42.8%, respectively, at 100% engine load. In addition, many researchers showed that NO_x emissions of diesel engines increased significantly with a PODE addition [29–31]. Thus, the blending ratio of PODE in diesel is not as high as possible.

By analyzing the previous research, many experiments have been carried out to investigate the effects of PODE in actual diesel engines. However, fundamental data about the combustion process and flame development in cylinders are still rare. There is a lack of relevant research on the explanation of soot formation from the perspective of basic combustion, especially visualization research. The combustion studies of PODE diesel blend fuels in a constant-volume chamber have limitations, because the inlet air flow is ignored. Accordingly, it is necessary to investigate the combustion process and the soot formation of PODE diesel blends in an optical engine. Therefore, the influence of different PODE blending ratio in blends (0%, 20%, 50% and 100% by volume) on the combustion characteristics of an optical engine under the injection pressures of 100 MPa, 120 MPa and 140 MPa and the injection timings of a 6-degree crank angle (°CA) before top dead center (BTDC), 9 °CA BTDC, 12 °CA BTDC and 15 °CA BTDC are investigated in this study. The fuel with a PODE blending ratio of 0 is diesel, which is used as the basic fuel for comparison. The PODE blending ratios of 20%, 50% and 100% selected in this study can complement the relevant research on the effects of neat PODE, small proportions and half proportions of PODE additions in diesel on the engine characteristics of the combustion process and soot emissions. This work attempts to provide an intuitive understanding of PODE and diesel blends on the combustion characteristics, combustion process and soot formation in an optical engine; supplement the results from the constant-volume chambers and may help in the development of PODE as a diesel additive.

2. Methodology

2.1. Test System

The test system was mainly composed of an optical engine, high-speed camera system, fuel supply system and control acquisition system. Figure 2 displays the experimental scheme of the optical engine system. Testing the optical engine in this research was modified from a 4-cylinder diesel engine; the third cylinder was selected as the lengthened working cylinder, and the other cylinders were abandoned. Table 1 displays the engine specifications. A transparent quartz glass was installed on the top of the piston, and its optical effective diameter was 71 mm. The material of the glass in the top of the piston was made out of quartz for higher heat resistance, a high transmittance of 95% in visible and 85% in ultraviolet, a high transmittance range of 185–3500 nm band, a low refractive index, a high hardness and mechanical strength, a smaller thermal expansion coefficient, oxidation resistance and chemical corrosion resistance. A 45° ultraviolet reflector was fixed on the hollow part of the engine block and piston body. The situation in the combustion chamber was recorded by a high-speed camera after being reflected by the 45° ultraviolet reflector through the transparent quartz glass. The camshaft gear was turned to adjust the valve timing. The optical engine was connected to the DC electric dynamometer through a coupling, and the dynamometer was the HZDZ-20 (rated power: 20 kW; Keda Co., Tianjin, China). This test used a DC dynamometer to automatically control the engine speed at 1200 r/min for abating the pollution of the reflector and for a longer analyzable combustion process measured in seconds. The engine compression ratio was reduced from the previous 17.5 to 11 by the modification from which it can protect against spray impingement on the glass on top of the piston and ensure that the laser sheet passes through the effective areas of the injector. Before the test, the cooling water temperature and intake air temperature needed to be heated to be 368 K and 398 K, respectively, to guarantee normal compression ignition combustion. When the quartz glass and reflector got contaminated, it was necessary to shut off the engine and wipe the glass and reflector to ensure the cleanliness and prepare for continuing the experiment.

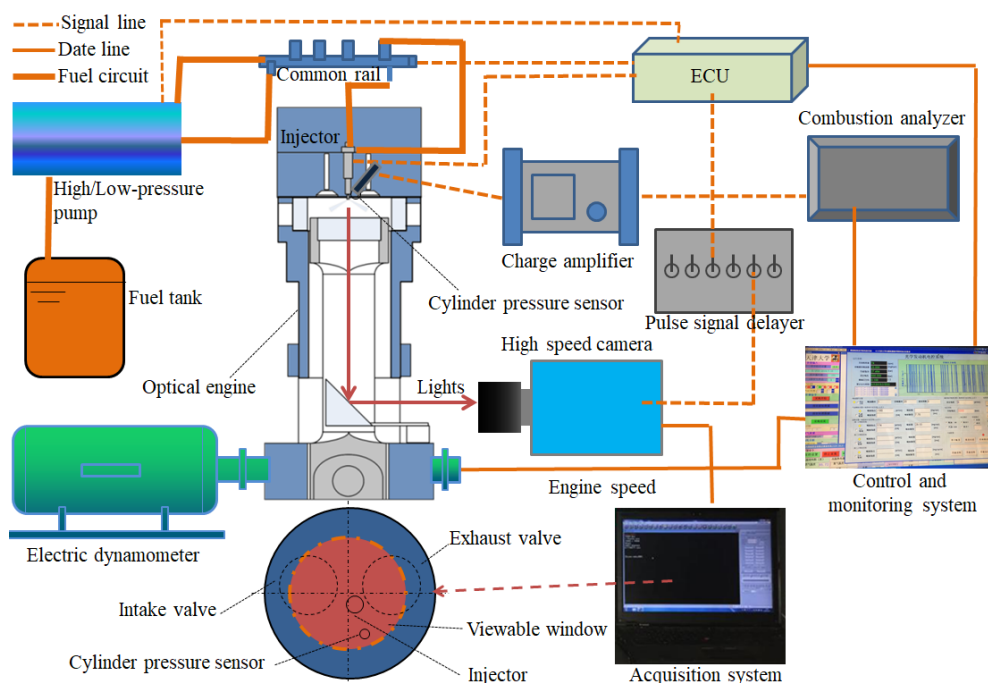


Figure 2. The experimental scheme of the optical engine system.

Table 1. Engine specifications.

Parameter	Value
Connecting rod length (mm)	155
Bore × Stroke (mm)	92 × 100
Displacement (L)	0.664
Swirl ratio	1.5
Valve number	2
Compression ratio	11

The Bosch high-pressure common rail direct injection fuel injection system was used in this study. The injector had 6 holes, the diameter of the nozzle hole was 150 µm and the spray cone angle was 150°. The injection quantity was 20 mg/cycle, which was calibrated and ensured a long enough experiment time with clean glass. Twenty cycles were set as the time between two consecutive injections for the following reasons. Firstly, there was enough time to remove the influence of the residual gas on the process of the in-cylinder combustion. Secondly, it can prevent the glass damage due to thermal stress and thermal fatigue. Finally, it can also avoid the glass pollution with combustion products. This study was carried out under 100, 120 and 140 MPa injection pressures and 6, 9, 12 and 15 °CA BTDC injection timings, respectively.

The data acquisition system not only needed to collect the cylinder pressure but also needed to collect the combustion images. Therefore, the cylinder pressures acquisition system and images acquisition system were included in the data acquisition system. The signals of the cylinder pressures were collected by the piezoelectric pressure sensor (6125C, Kistler, Switzerland) and then input into the combustion analyzer through a charge amplifier. At the same time, the encoder input the crank angle signal into the combustion analyzer. The fuel injection system sent out the fuel injection signal, as well as the image acquisition signal at the same time. The image acquisition signal was time-adjusted by the delay trigger, and the high-speed CMOS camera (FASTCAM-SA5, Photron Co., Tokyo, Japan) was triggered to acquire the combustion process in-cylinder. The camera was equipped with a Nikon len (Micro 50 mm f/1.4). When the combustion image was saved after the end of the injection in each experimental plot, each image acquisition was completed. The frame rate of the camera taking pictures was 20,000 frames per second (fps), and the resolution of the images was 512 pixels × 512 pixels. The crank angle interval between two adjacent images was 0.36 °CA when the engine was running at the speed of 1200 r/min. For each working condition, the combustion images were measured no less than 10 times, and the in-cylinder pressures were measured 30 times. The average value of multiple repeated test data was used as the final result to analyze the flame combustion characteristics of the different blends in an optical engine under various working conditions. Therefore, the reliability and accuracy of the experimental results could be ensured in this way.

2.2. Data Processing

Self-compiled MATLAB procedures were used to analyze the combustion images obtained from the high-speed camera system in this study. A two-color method was used to analyze the images, and then, the distributions of spatial temperature and spatial KL in-cylinder of the optical engine can be obtained. KL was used to characterize the overall soot concentration in the cylinder. The light radiation of ϵ_λ is a function of the KL and the wavelength λ [32], which is shown as Equation (1):

$$\epsilon_\lambda = 1 - \exp\left(-\frac{KL}{\lambda^a}\right) \quad (1)$$

K represents the absorption coefficient, which is approximately proportional to the soot concentration. L represents the geometric thickness of the optical axis in the flame

detection direction. α is a constant, which represents the visible wavelength, and it is assumed to be 1.39 in many studies [33–36].

The soot radiation intensity $I(\lambda, T)$ is a function of the temperature T and wavelength λ , according to the Planck Radiation Law, which is shown as Equation (2), where C_1 is the constant $-1.1910439 \times 10^{-16} \text{ Wm}^2\text{sr}^{-1}$, and C_2 is the Planck's constant $-1.4388 \times 10^2 \text{ mK}$. T_a is the temperature obtained by calculating the radiation intensity when the object is equal to the black body, which is called the brightness temperature.

$$I(\lambda, T) = \epsilon_\lambda \frac{C_1}{\lambda^5} \exp\left(-\frac{C_2}{\lambda T_a}\right) \quad (2)$$

The calculation methods of T and KL are Equations (3) and (4):

$$\left\{1 - \exp\left[-\frac{C_2}{\lambda_1} \left(\frac{1}{T_{a\lambda_1}} - \frac{1}{T}\right)\right]\right\}^{\lambda_1^q} = \left\{1 - \exp\left[-\frac{C_2}{\lambda_2} \left(\frac{1}{T_{a\lambda_2}} - \frac{1}{T}\right)\right]\right\}^{\lambda_2^q} \quad (3)$$

$$KL = -\lambda_1^q \ln\left\{1 - \exp\left[-\frac{C_2}{\lambda_1} \left(\frac{1}{T_{a\lambda_1}} - \frac{1}{T}\right)\right]\right\} \quad (4)$$

Based on the in-cylinder pressure signal collected by the piezoelectric pressure sensor, the heat release rate (HRR) and combustion temperature can be calculated by the simplified heat release model [37,38]. The HRR and in-cylinder temperature are calculated by Equations (5) and (6), where κ represents the specific heat ratio, and the value is 1.35. V represents the instantaneous cylinder volume. p represents the in-cylinder pressure, m represents the charging mass and c_v represents the constant-volume-specific heat.

$$\frac{dQ}{d\varphi} = \frac{\kappa}{\kappa - 1} p \frac{dV}{d\varphi} + \frac{1}{\kappa - 1} V \frac{dp}{d\varphi} \quad (5)$$

$$\frac{dT}{d\varphi} = \frac{1}{mc_v} \left(\frac{dQ}{d\varphi} - p \frac{dV}{d\varphi} \right) \quad (6)$$

2.3. The Properties of the Test Fuels

There were four fuels in this study. PODE was blended with diesel in a 0%, 20%, 50% and 100% ratio by volume, which were named D100, P20, P50 and P100, respectively. The PODE used in this study was mainly composed of PODE₂, PODE₃, PODE₄ and other components. The proportion of each component was 12%, 46%, 34% and 8% by mass, respectively. The PODE used in this study was bought from Shandong Shanghekai Chemical Co., Ltd. in Jinan, China. The diesel was bought from the market of China National Petroleum Corporation in Xi'an, China. According to the oxygen content of each component of PODE, the minimum oxygen content of PODE used in this test was 43.5%. The properties of the four test fuels are shown in Table 2, and the distillation temperatures of the diesel and PODE are shown in Table 3.

Table 2. Properties of the test fuels.

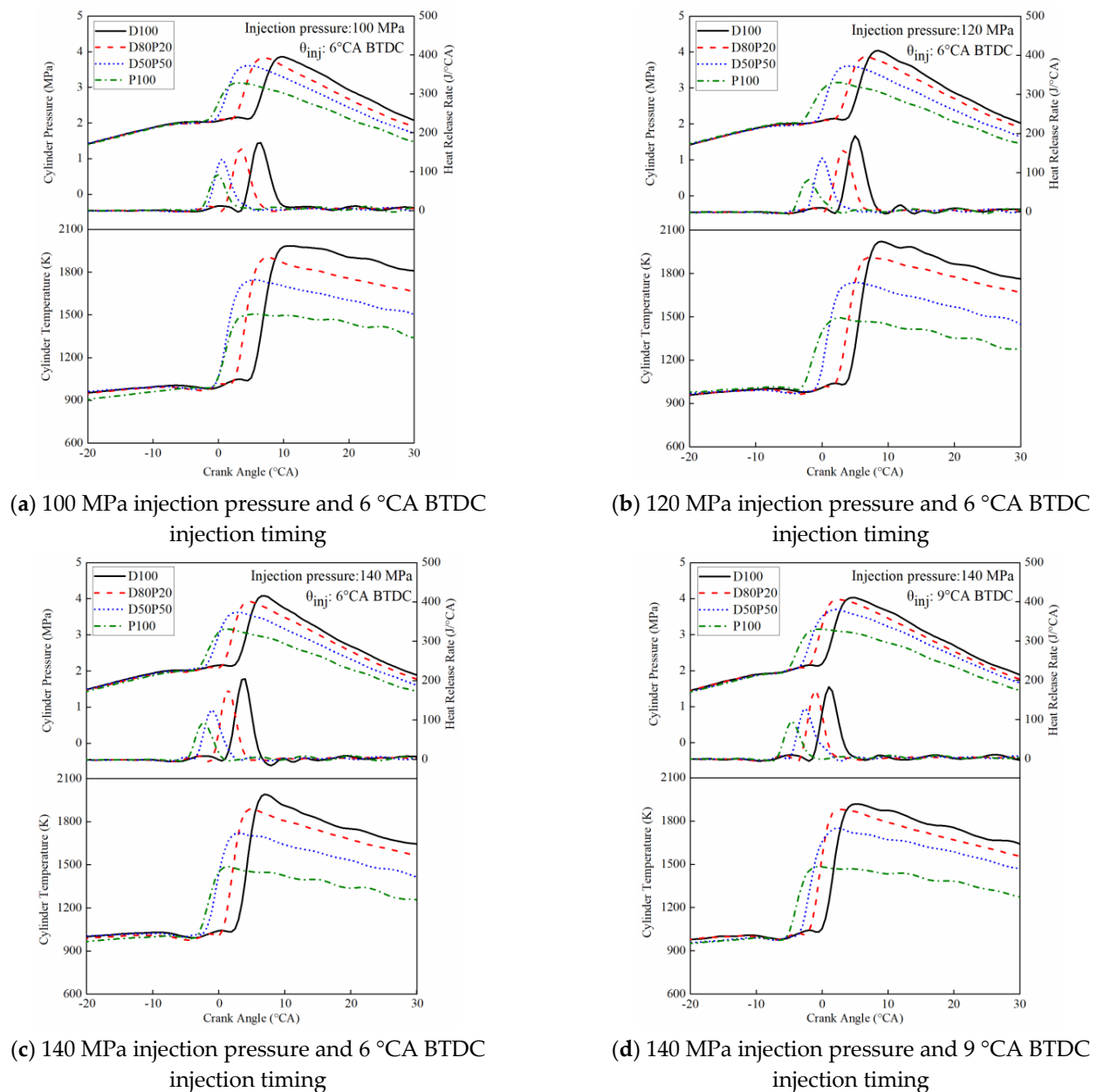
Properties	D100	P20	P50	P100
Density (g/cm ³)	0.832	0.908	0.952	1.072
Viscosity at 20 °C (mm ² /s)	3.34	3.05	2.66	1.98
Cetane number	50	54	61	72
Lower heating value (LHV) (MJ/kg)	44.94	38.79	35.38	25.81
Oxygen content (%)	0	10.3	25.7	43.5

Table 3. Volatility of the diesel and PODE.

Distillation Temperature	D100	PODE
Initial boiling point (K)	444	422
50% vol recovery (K)	548	450
95% vol recovery (K)	635	513
Final boiling point (K)	648	525

3. Discussion for Thermodynamic Combustion Characteristics

The zero point of the heat release rate from (HRR) negative to positive was defined as the SOC. The zero point of HRR from positive to negative was defined as the end of combustion (EOC) in this study. The heat release ignition delay (HRID) was defined as the period between the start of injection (SOI) and SOC, and CD was the period between the SOC and EOC. The combustion pressure, HRR and combustion temperature in-cylinder of the four test fuels under different injection pressures and timings are shown in Figure 3.

**Figure 3.** Cont.

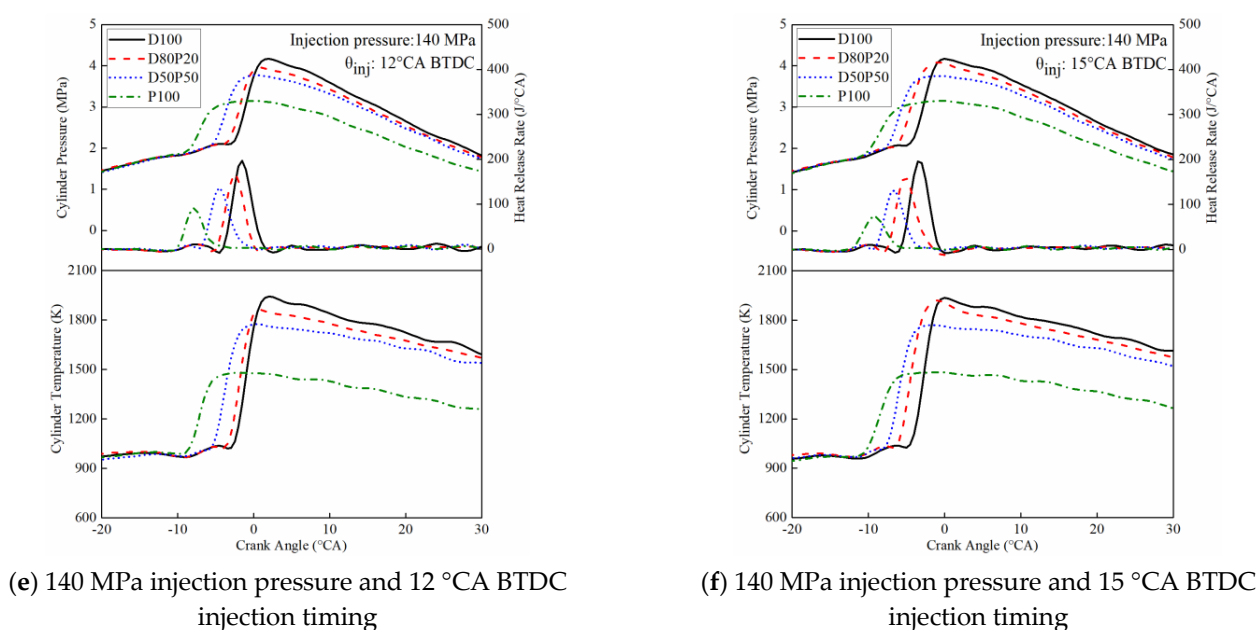


Figure 3. The cylinder pressures, HRR and cylinder temperature.

Under the same conditions, the combustion pressure, HRR and combustion temperature of the blends all decreased as the PODE blending ratio increased. D100 always had the highest peak HRR (PHRR), peak combustion pressure (PCP) and peak combustion temperature (PCT). Meanwhile, P100 always had the lowest PCP, PHRR and PCT. The higher oxygen content of PODE can release a large number of active free radicals during the combustion stage thereby promotes complete combustion and heat release [30,39,40]. The fuel injection quantity was fixed at 20 mg/cycle. The LHV of PODE was 25.81 MJ/kg lower than the 44.94 MJ/kg of diesel. The effect of PODE on promoting the combustion quality weakened, and the negative effect of LHV was dominant.

It can be clearly seen that the SOC of the blend was advanced with the addition of PODE. The CN of PODE is 72, which is much higher than that of diesel. The CN is related to the fuel ignitability. The higher the CN of fuels, the easier they are to be compression-ignited [41]. Therefore, as the ratio of PODE in the fuel blend increased, the CN increased, and the HRID significantly shortened. In addition, the HRIDs of the four test fuels shortened as the injection pressure increased when the injection timing was fixed at 6 °CA BTDC. It was because increasing the injection pressure makes the formation of the mixture more uniform, which can make the in-cylinder combustion much easier [42]. Moreover, the CD of the blend fuels decreased with the PODE increasing, which indicated that the addition of PODE sped up the in-cylinder combustion and promoted the concentrated heat release.

4. Discussion for Optical Combustion Characteristics

Figure 4 shows the in-cylinder combustion images of the test fuels under the injection pressure of 100 MPa and the injection timing of 6 °CA BTDC. It was obvious that the flames of the four fuels all appeared first at the edge of the combustion chamber. It can be advisably understood from two aspects: the spray atomization reduced the temperature near the injector to lift the condition of flammable limits in an area near the center of the injector. The combustible mixture appeared first in front of the spray, which was nearby the edge of the combustion chamber. Then, the flame front moved to the area of the injector nearby, and the entire combustion chamber was filled with flame quickly. Immediately afterwards, the combustion areas became smaller, and the combustion processes entered the late-combustion stage. The luminescence ignition delay (LID) was defined as the period between the SOI and the timing of the first combustion images. Due to the high CN of

PODE, it can be seen from the figures that the crank angle of the first combustion images was advanced, and the LID shortened with the increasing of the PODE blending ratio in the blends. The LID and the HRID were different concepts, and the LID was later than HRID normally. The difference between the LID and the HRID was related to the start time of fuel low-temperature reaction for the initial pressure transfer timing and initial luminescence emission time.

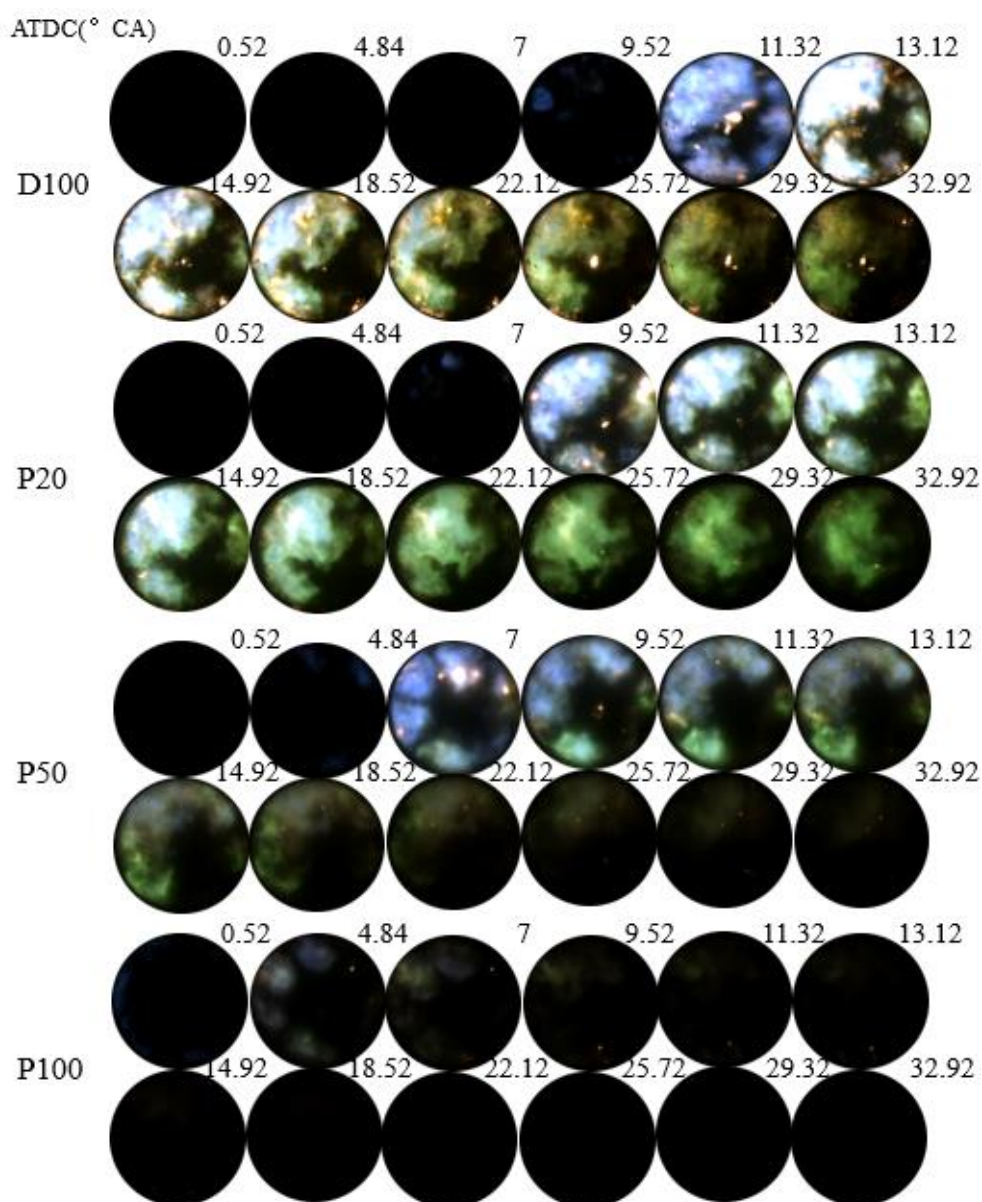


Figure 4. The combustion images (Injection pressure: 100 MPa; Injection timing: 6 °CA BTDC).

The natural flame luminosity of fuels during combustion is mainly divided into chemiluminescence and soot incandescence, and the intensity of soot incandescence is much stronger than that of chemiluminescence [43]. It is generally believed that the “blue flame” symbolizes the chemiluminescence of HCHO converting into CO in high-temperature areas, and the “yellow flame” represents the incandescent light of soot [44,45]. The yellow flame of the blends decreased with the increasing of the PODE ratio in the blends, and almost no yellow flame was observed in the flames of P100. This was mainly due to the fact that PODE does not contain C-C bonds and has a high oxygen content, which had a positive effect on inhibiting soot formation. It should be noted that there

were yellow dots or bright yellow areas in the center area or the edge of the combustion images. The amount of retained fuel in the area close to the nozzle or the edge of the combustion chamber increased, so that the fuel combustion was insufficient, and yellow flames were generated. In the late stage of fuel injection, the injector needle valve was seated, and the injection pressure dropped. Therefore, the fuel spray atomization quality in the area near the center of the injector was poor, which was not conducive to combustion. Further, with the addition of PODE, the yellow dots in the center area or the edge area of the image decreased. The lower viscosity and distillation temperature of PODE improved the atomization quality and promoted the full combustion of the blended fuel, and thereby, the soot formation was reduced.

The spatial temperature and spatial *KL* distributions of the combustion flames in an optical engine cylinder can be obtained by using the two-color method. The images of temperature and *KL* distributions under the 6 °CA BTDC injection time and 100-MPa injection pressure individually are shown in Figures 5 and 6. The temperature range of the spatial temperature distribution images was between 1500 K and 2400 K. It appeared as dark blue in the images when the combustion temperature was lower than 1500 K and bright yellow when the combustion temperature was higher than 2400 K. The *KL* range was between 0 and 0.0002.

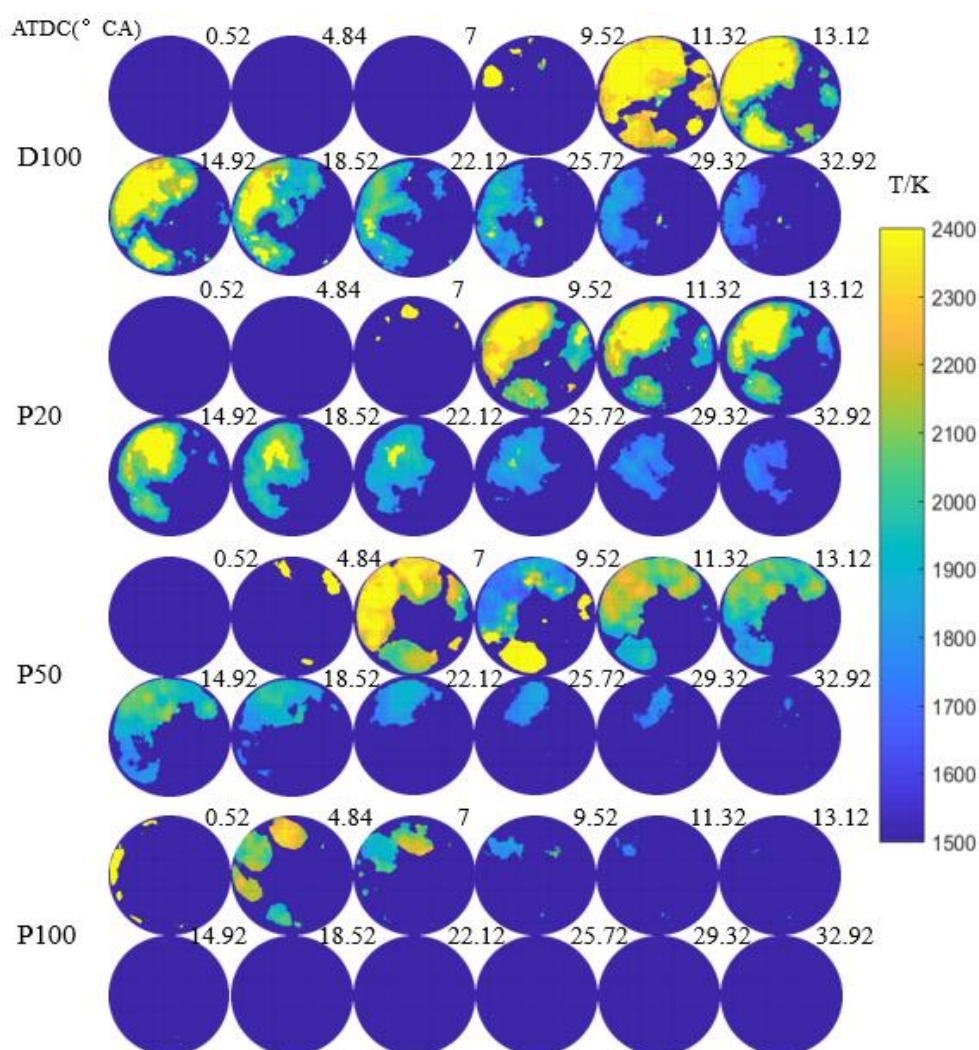


Figure 5. Spatial temperature distribution (Injection pressure: 100 MPa; Injection timing: 6 °CA BTDC).

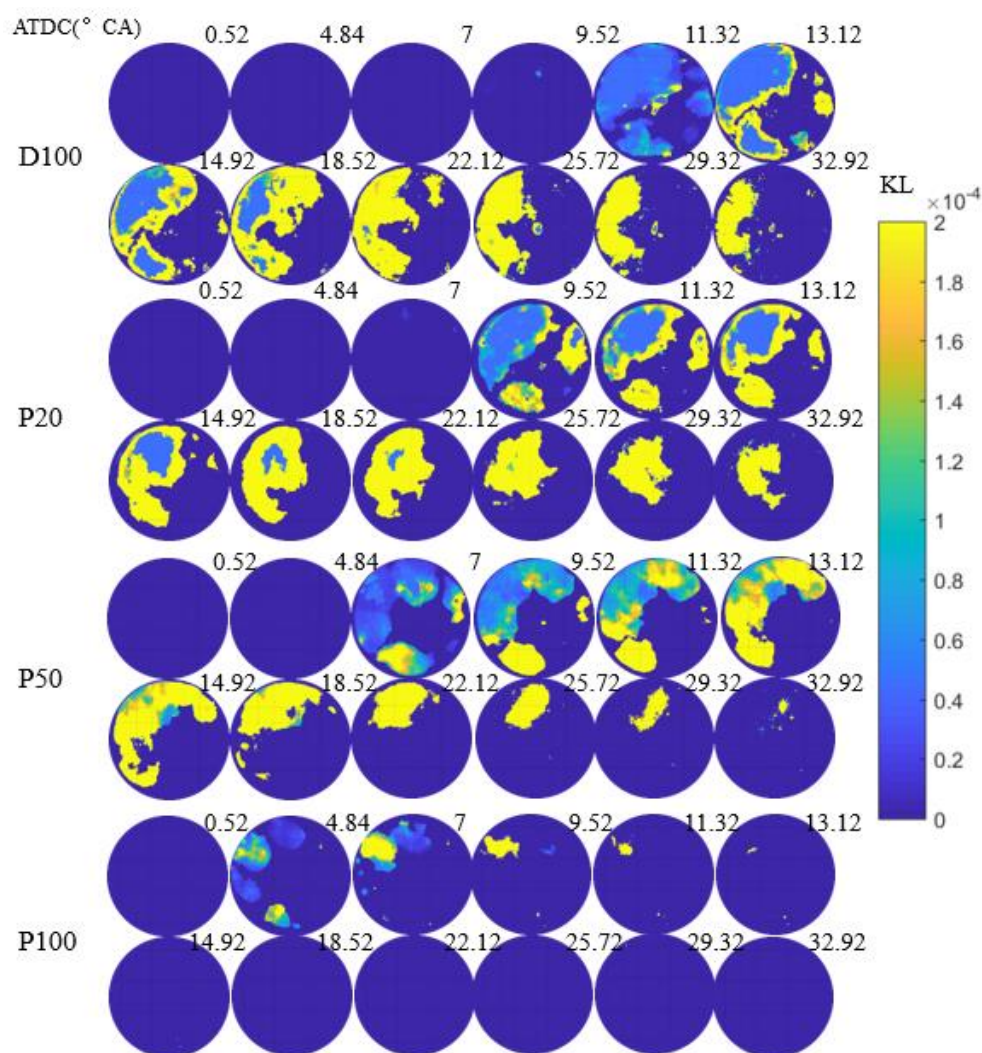


Figure 6. Spatial KL distribution (Injection pressure: 100 MPa; Injection timing: 6 °CA BTDC).

Comparing and analyzing Figures 4 and 5, it can be found that the spatial temperature distribution images of the four test fuels were all in yellow or bright yellow in the early stage of the combustion, indicating the high flame temperature. This can be explained by the fact that, in the region where the combustion flame first appeared, the atomization quality of the blends was high, and the amount of the air–fuel mixture was sufficient, which accelerated the combustion heat release and led to a high flame temperature. In the early stage of combustion, called the premixed combustion stage, the high temperature zone expanded rapidly. In the intermediate or late stage of combustion, called the diffusion combustion stage, the high-temperature zone shrank gradually. With the increasing of the PODE blending ratio, the proportion of the high-temperature region in the spatial temperature distribution images gradually decreased, indicating that the flame temperature decreased. The phenomenon that the in-cylinder temperature decreased with the addition of PODE was consistent with the results calculated by the in-cylinder pressure in Section 3.

It can be seen from Figure 6 that the soot contours were small in the early stage due to the high temperature, which can be observed in Figure 5. The research showed that a high temperature can strengthen the oxidation of soot [46]. In the stage of diffusion combustion, the formation of soot gradually increased. With the addition of PODE, the area of soot decreased sharply. There were several reasons for this. Firstly, no C–C bond of PODE inhibited the soot precursor formation. Secondly, PODE had a high oxygen content of 43.5, which can accelerate the complete combustion of the blends. Thirdly, the addition of PODE

improved the spray quality, which resulted in low soot formation. Lastly, the addition of PODE narrowed the combustion regions to reduce the soot formation regions.

The combustion images under the injection pressure of 140 MPa and the injection timings of 6 °CA BTDC and 12 °CA BTDC are displayed in Figures 7 and 8. In general, the flame structures and the development processes of the four test fuels were similar to those under 100-MPa injection pressure and 6 °CA BTDC injection timing shown in Figure 4. Comparing Figure 7 with Figure 4, it can be found that the luminescence SOC of the four test fuels advanced as the injection pressure increased, since the mixture of air and fuel was improved, and the flammability limit of the mixture appeared earlier. In addition, the proportions of yellow flames in the process of combustion development for D100, P20 and P50 were greatly narrowed, indicating that increasing the injection pressure improved the in-cylinder combustion quality and reduced the soot formation. However, the effect of increasing the injection pressure on the combustion flame was not obvious for P100. The luminescence timings of the four test fuels became earlier as the injection timing advanced by comparing Figure 8 with Figure 7. However, the combustion process of P100 was almost completed before TDC under an injection pressure of 140 MPa and injection timing of 12 °CA BTDC, which was negatively conducive to the engine performance.

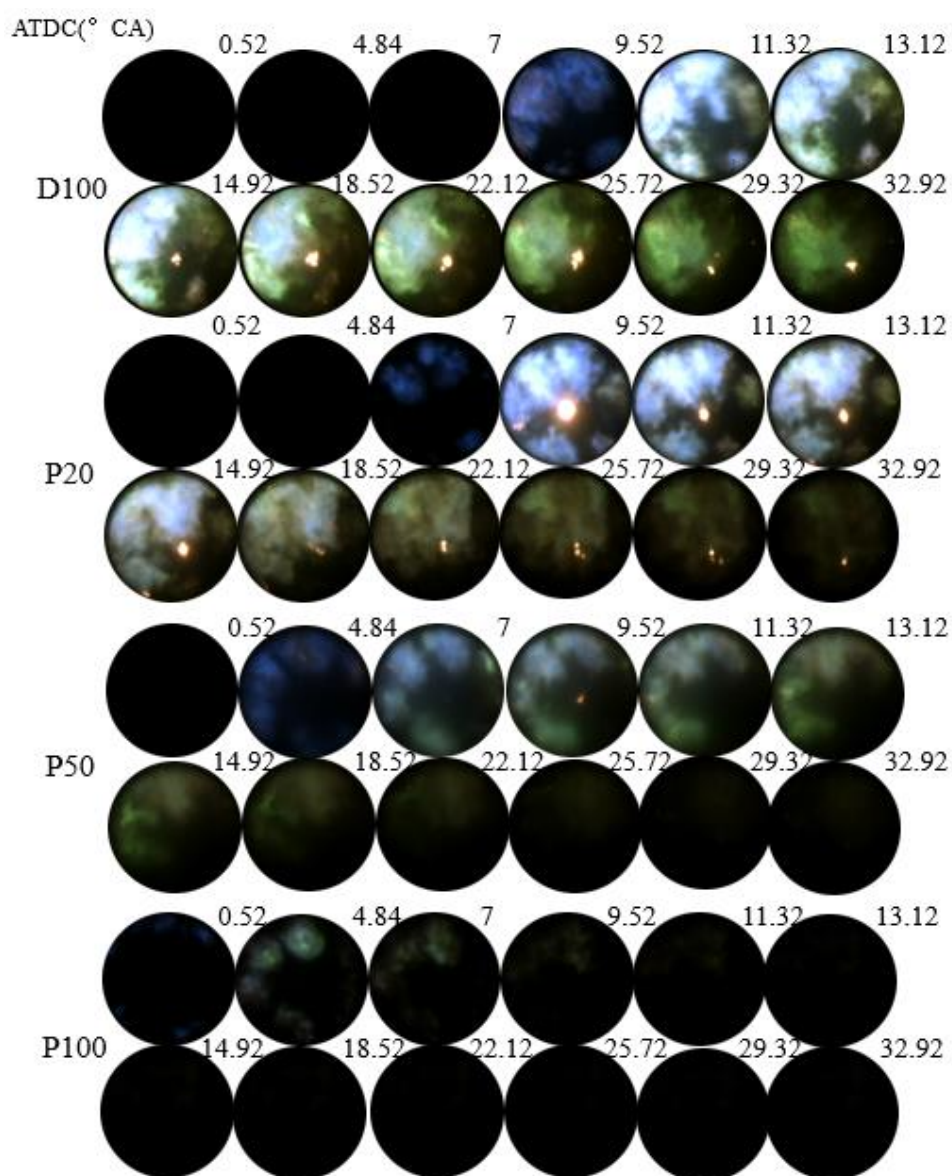


Figure 7. The combustion images (Injection pressure: 140 MPa; Injection timing: 6 °CA BTDC).

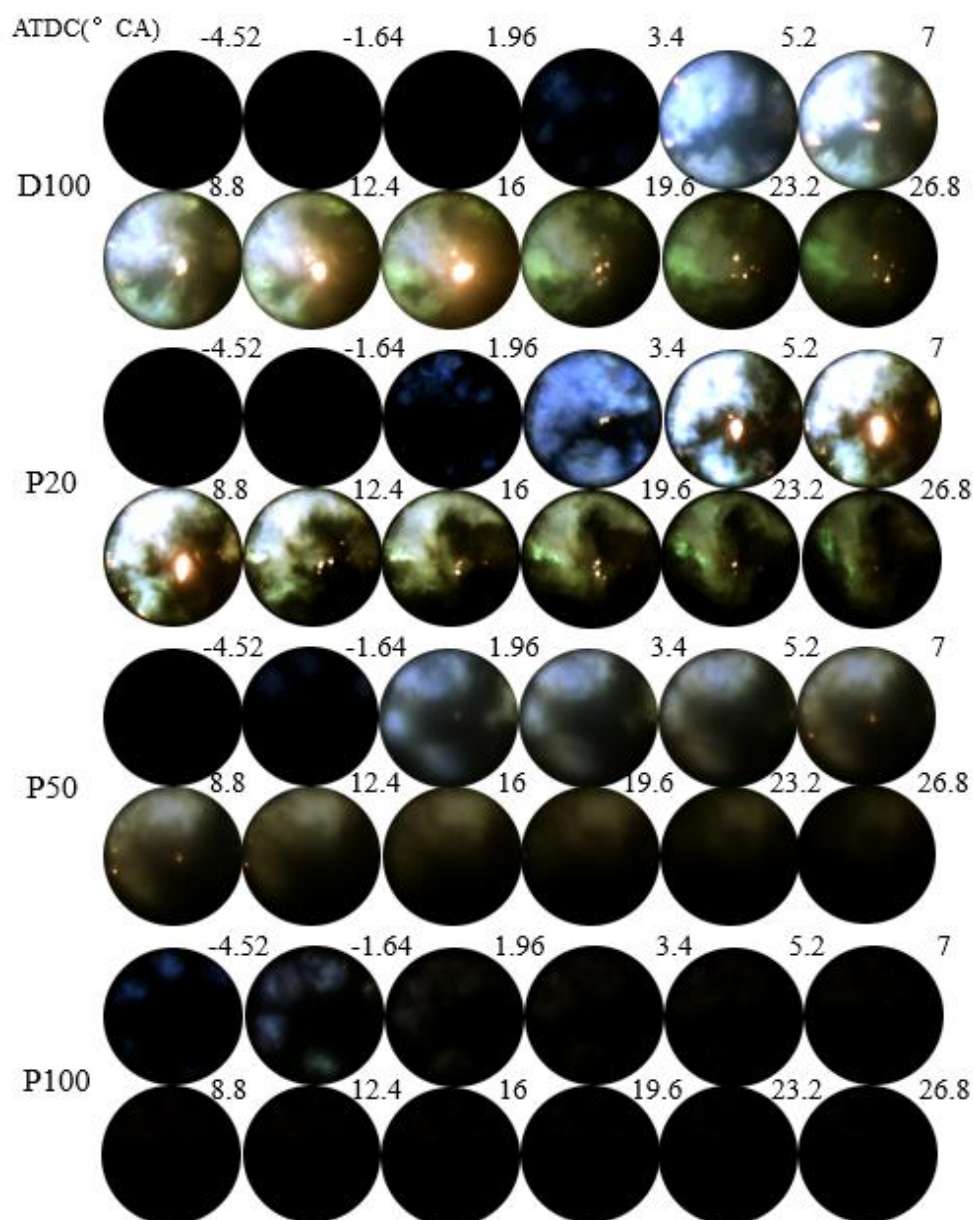


Figure 8. The combustion images (Injection pressure: 140 MPa; Injection timing: 12 °CA BTDC).

The combustion development process of P20 was discussed thoroughly in this paper. The combustion flame, spatial temperature distribution and spatial *KL* distribution images of P20 under various injection pressures are shown in Figures 9–11. It can be seen from the combustion flame images that the flame spreading speed was obviously accelerated with the increasing of the injection pressure in the early combustion stage. Increasing the injection pressure made the fuel beam obtain a higher initial kinetic energy and strengthened the collision between the fuel and air molecules, which increased the spread of the spray and reduced the particle sizes. Therefore, increasing the injection pressure can improve the atomization quality of P20, thereby increasing the intensity of the premixed combustion. Obviously, the proportion of the high-temperature region in the spatial temperature distribution images increased with the increasing of the injection pressure. In the premixed combustion stage, the soot formation decreased greatly with the increasing of the injection pressure, while there was almost no change in the diffusion combustion stages.

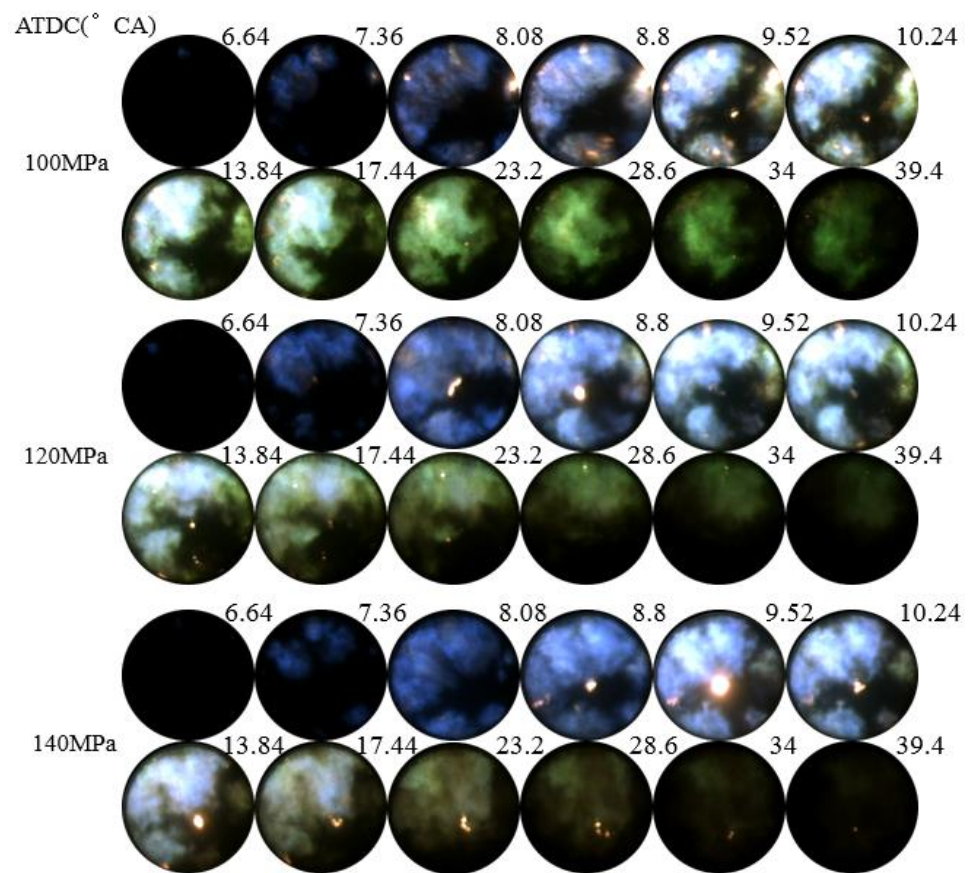


Figure 9. The combustion images of P20 at 6°CA BTDC injection timing.

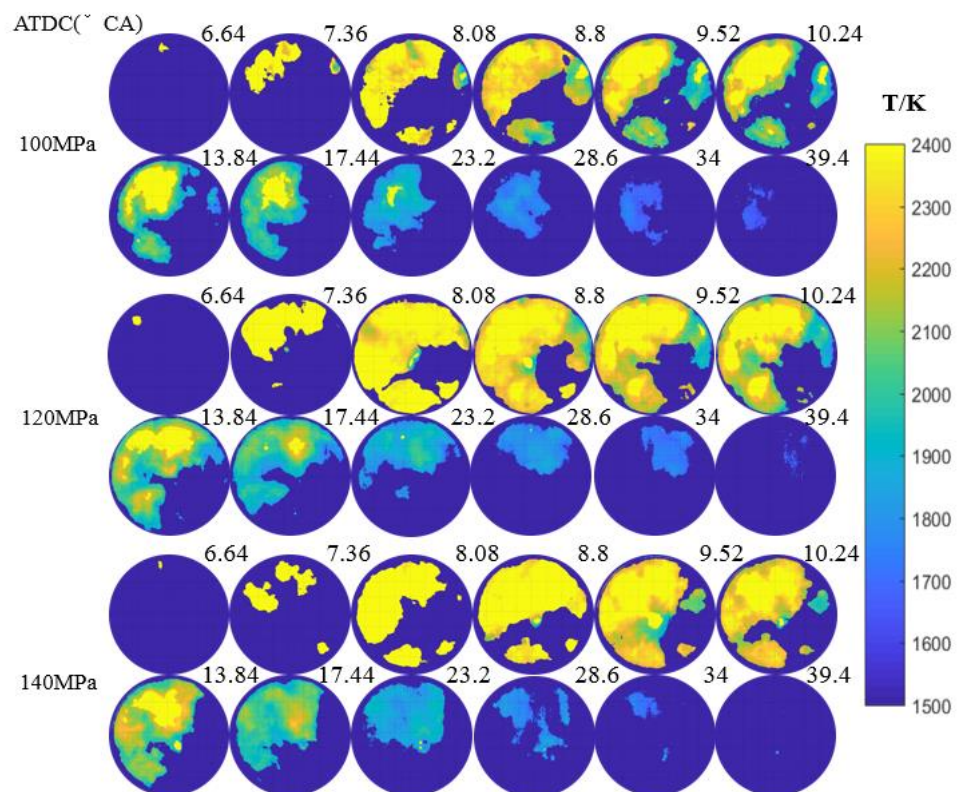


Figure 10. Spatial temperature distribution of P20 at 6°CA BTDC injection timing.

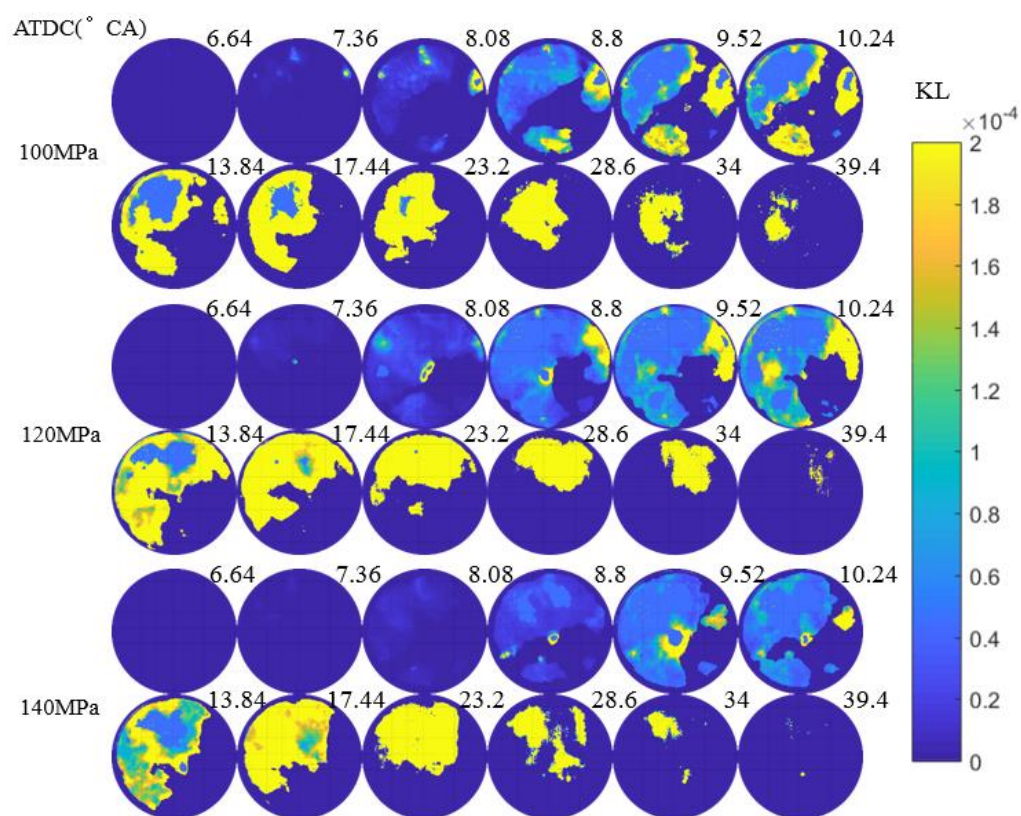
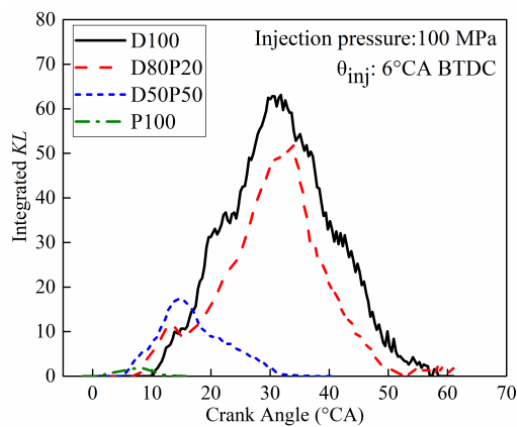


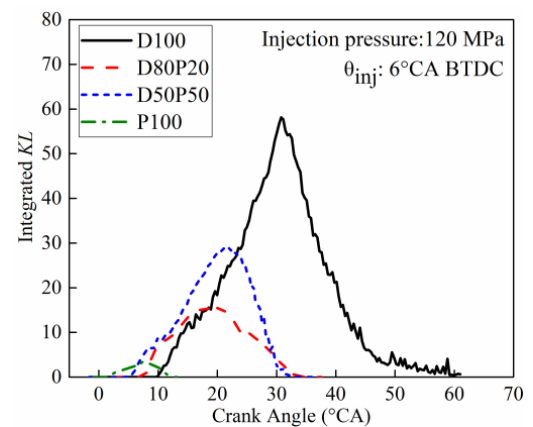
Figure 11. Spatial KL distribution of P20 at 6 °CA BTDC injection timing.

Figure 12 displays the integrated KL curve of four test fuels under various injection conditions. The integrated KL was defined as the sum of the KL values of each image, which represented the change of soot generation in cylinders with a crank angle. Adding PODE into diesel can greatly reduce the soot emissions of the blends under any injection condition. For D100, both advancing the injection timing and increasing the injection pressure reduced the value of the integrated KL and thereby reduced the soot formation. For P20, the soot formation was markedly reduced when the injection pressure increased from 100 MPa to 120 MPa, while there was no significant change in the soot formation by continuing to increase the injection pressure and advance the injecting timing. Changing the injection conditions had an insignificant effect on the soot formation for P50 and P100. It can be concluded that, when 20% PODE was blended with diesel, both the injection conditions (spray atomization quality) and chemical properties of the blend affected the soot formation. When the blending ratio of PODE was raised to 50% and 100%, the chemical properties of the blends played a leading role in the soot formation, while the change of the injection conditions had an inconspicuous effect on it.

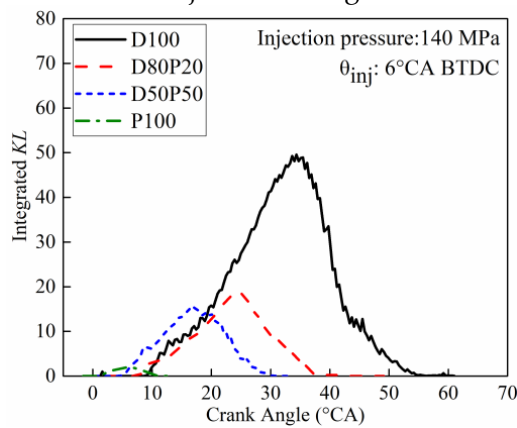
The integrated natural flame luminosity (INFL) was defined as the sum of the total intensity value in each image. The INFL of the test fuels under various injection pressures are given in Figure 13. The natural luminosity of the flame during the combustion duration was composed of chemiluminescence and soot incandescence. The INFL reduced obviously with the adding of PODE due to the decreased soot formation. The addition of PODE decreased the soot formation, which was conducive to reducing the heat radiation and INFL. Further, the flame area of the blends decreased with the addition of PODE, which can be seen from the combustion flames in Figures 7 and 8, and therefore, the INFL decreased.



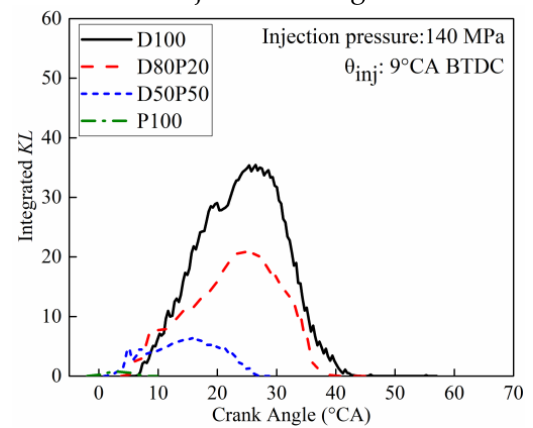
(a) 100 MPa injection pressure and 6 °CA BTDC injection timing



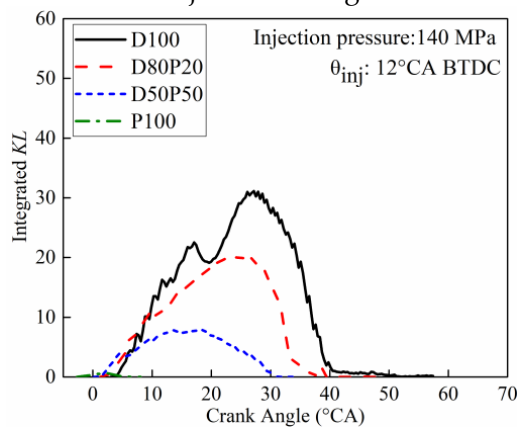
(b) 120 MPa injection pressure and 6 °CA BTDC injection timing



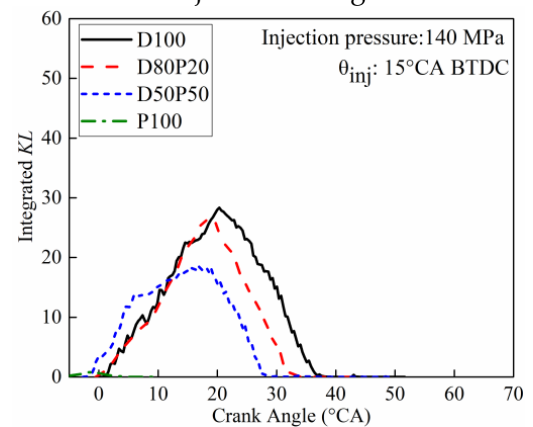
(c) 140 MPa injection pressure and 6 °CA BTDC injection timing



(d) 140 MPa injection pressure and 9 °CA BTDC injection timing



(e) 140 MPa injection pressure and 12 °CA BTDC injection timing



(f) 140 MPa injection pressure and 15 °CA BTDC injection timing

Figure 12. Integrated KL.

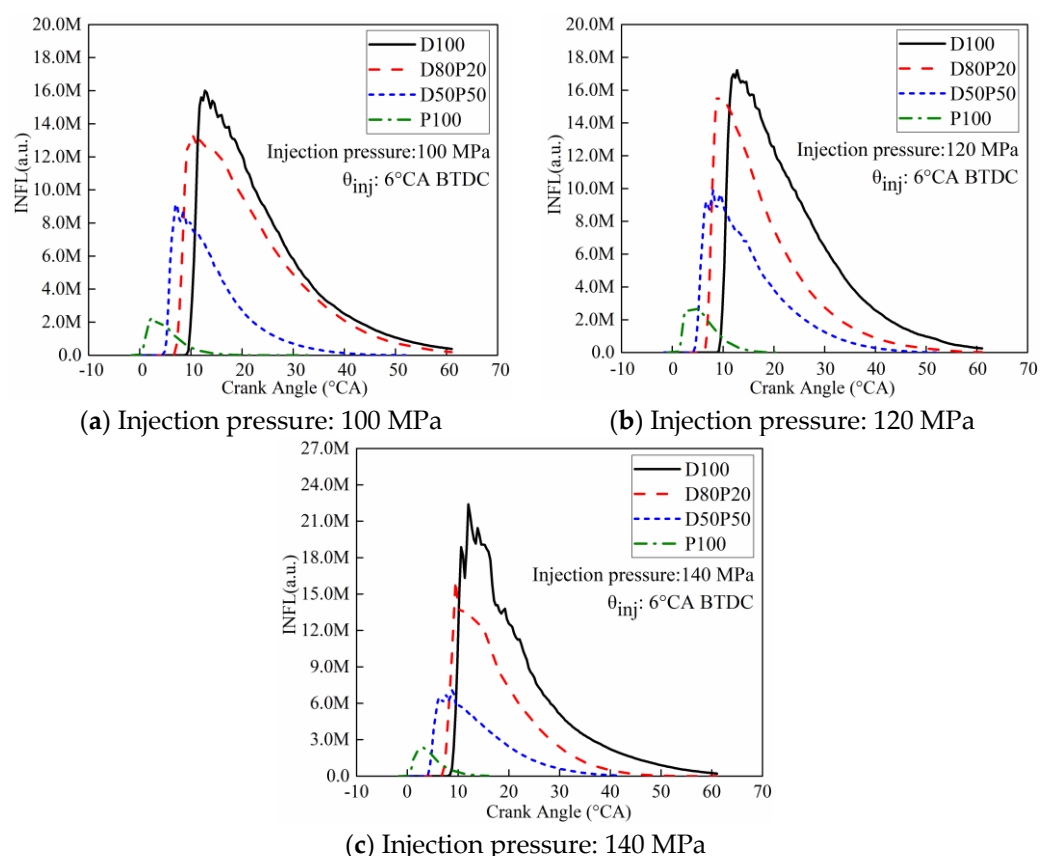


Figure 13. Integrated natural flame luminosity (Injection timing: 6°CA BTDC).

5. Conclusions

The combustion study of polyoxymethylene dimethyl ethers and diesel blend fuels was comprehensively investigated on an optical engine. The conclusions of the experimental study are as follows:

(1) The ID of the blends shortened as the PODE blending ratio increased due to a higher CN of PODE. The peak heat release rate, peak cylinder pressure and peak cylinder temperature of the blends decreased with the ratio of PODE due to the lower LHV of PODE in the case of a fixed fuel supply. Adding PODE into diesel can significantly reduce the soot formation and the integrated natural flame luminosity under any injection conditions due to the excellent physical and chemical properties of PODE.

(2) For P20, both the injection conditions (spray atomization quality) and chemical properties of the blends affected the soot formation. When the blending ratio of PODE was 50% and 100%, the chemical properties of the blends played a leading role in soot formation while the change of the injection conditions had an inconspicuous effect on them. Thus, combining P20 and the optimized injection strategy had a satisfactory effect on the characteristics of combustion and emission, which was impossible for P50 and P100.

(3) The larger the PODE blending ratio in diesel, the greater the reduction in the soot emissions of diesel engines. PODE has a lower heating value of 25.81 MJ/kg, which is much lower than the 44.94 MJ/kg of diesel. A high ratio of PODE in blends may affect the power performance of the diesel engine. P20 showed excellent characteristics in a comprehensive evaluation of the combustion and soot reduction.

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

Funding: This research was funded by the Innovation Capability Support Program of Shaanxi, grant number 2021TD-28, Key Research and Development Program of Shaanxi, grant number 2019ZDLGY15-07, Youth Innovation Team of Shaanxi Universities, and Yulin Science and Technology project, grant number CXY-2020-024.

Data Availability Statement: Data is available upon request to the corresponding authors.

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

References

1. Zhao, Y.; Xu, Z.; Chen, H.; Fu, Y.; Shen, J. Mechanism of chain propagation for the synthesis of polyoxymethylene dimethyl ethers. *J. Energy Chem.* **2013**, *22*, 833–836. [\[CrossRef\]](#)
2. Zhao, Q.; Wang, H.; Qin, Z.; Wu, Z.; Wu, J.; Fan, W.; Wang, J. Synthesis of polyoxymethylene dimethyl ethers from methanol and trioxymethylene with molecular sieves as catalysts. *J. Fuel Chem. Technol.* **2011**, *39*, 918–923. [\[CrossRef\]](#)
3. Li, H.; Song, H.; Zhao, F.; Chen, L.; Xia, C. Chemical equilibrium controlled synthesis of polyoxymethylene dimethyl ethers over sulfated Titania. *J. Energy Chem.* **2015**, *24*, 239–244. [\[CrossRef\]](#)
4. Liu, H.; Wang, Z.; Wang, J.; He, X. Improvement of emission characteristics and thermal efficiency in diesel engines by fueling gasoline/diesel/PODEn blends. *Energy* **2016**, *97*, 105–112. [\[CrossRef\]](#)
5. Burger, J.; Siegert, M.; Strofer, E.; Hasse, H. Poly(oxyethylene) dimethyl ethers as components of tailored diesel fuel: Properties, synthesis and purification concepts. *Fuel* **2010**, *89*, 3315–3319. [\[CrossRef\]](#)
6. Che, W.; Noor, M.; Mamat, R. Biodiesel as alternative fuel for marine diesel engine applications: A review. *Renew. Sustain. Energy Rev.* **2018**, *94*, 127–142.
7. Veljkovic, V.B.; Biberdzic, M.O.; Bankovicilic, I.B.; Djalovic, I.G.; Tasic, M.B.; Njezic, Z.B.; Stamenkovic, O.S. Biodiesel production from corn oil: A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 531–548. [\[CrossRef\]](#)
8. Sakthivel, R.; Ramesh, K.; Purnachandran, R.; Shameer, P.M. A review on the properties, performance and emission aspects of the third generation biodiesels. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2970–2992. [\[CrossRef\]](#)
9. Liu, J.; Wang, H.; Li, Y.; Zheng, Z.; Xue, Z.; Shang, H.; Yao, M. Effects of diesel/PODE (polyoxymethylene dimethyl ethers) blends on combustion and emission characteristics in a heavy duty diesel engine. *Fuel* **2016**, *177*, 206–216. [\[CrossRef\]](#)
10. Xie, M.; Ma, Z.; Wang, Q.; Liu, J.; Liu, S. Investigation of Engine Combustion and Emission Performance Fuelled with Neat PODE and PODE/Diesel Blend. *J. Xi'an Jiaotong Univ.* **2017**, *51*, 32–37.
11. Liu, H.; Wang, Z.; Zhang, J.; Wang, J.; Shuai, S. Study on combustion and emission characteristics of Polyoxymethylene Dimethyl Ethers/diesel blends in light-duty and heavy-duty diesel engines. *Appl. Energy* **2017**, *185*, 1393–1402. [\[CrossRef\]](#)
12. Chen, H.; Su, X.; Li, J.; Zhong, X. Effects of gasoline and polyoxymethylene dimethyl ethers blending in diesel on the combustion and emission of a common rail diesel engine. *Energy* **2019**, *171*, 981–999. [\[CrossRef\]](#)
13. Chen, H.; He, J.; Hua, H. Investigation on combustion and emission performance of a common rail diesel engine fueled with diesel/biodiesel/polyoxymethylene dimethyl ethers blends. *Energy Fuels* **2017**, *31*, 11710–11722. [\[CrossRef\]](#)
14. Pellegrini, L.; Marchionna, M.; Patrini, R.; Florio, S. Emission performance of neat and blended polyoxymethylene dimethyl ethers in an old light-duty diesel car. *SAE Tech. Pap.* **2013**. [\[CrossRef\]](#)
15. Chen, H.; He, J.; Chen, Z.; Geng, L. A comparative study of combustion and emission characteristics of dual-fuel engine fueled with diesel/methanol and diesel–polyoxymethylene dimethyl ether blend/methanol. *Process Saf. Environ. Prot.* **2021**, *147*, 714–722. [\[CrossRef\]](#)
16. Kang, M.; Song, H.; Jin, F.; Chen, J. Synthesis and physicochemical characterization of polyoxymethylene dimethyl ethers. *J. Fuel Chem. Technol.* **2017**, *45*, 837–845. [\[CrossRef\]](#)
17. Liu, H.; Ma, X.; Li, B.; Chen, L.; Wang, Z.; Wang, J. Combustion and emission characteristics of a direct injection diesel engine fueled with biodiesel and PODE/biodiesel fuel blends. *Fuel* **2017**, *209*, 62–68. [\[CrossRef\]](#)
18. Liu, J.; Shang, H.; Wang, H.; Zheng, Z.; Wang, Q.; Xue, Z.; Yao, M. Investigation on partially premixed combustion fueled with gasoline and PODE blends in a multi-cylinder heavy-duty diesel engine. *Fuel* **2017**, *193*, 101–111. [\[CrossRef\]](#)
19. Chen, H.; Su, X.; He, J.; Xie, B. Investigation on combustion and emission characteristics of a common rail diesel engine fueled with diesel/n-pentanol/methanol blends. *Energy* **2019**, *167*, 297–311. [\[CrossRef\]](#)
20. Park, W.; Park, S.; Rolf, D.; Reitz, R.D.; Kurtz, E. The effect of oxygenated fuel properties on diesel spray combustion and soot formation. *Combust. Flame* **2017**, *180*, 276–283. [\[CrossRef\]](#)
21. Li, D.; Gao, Y.; Liu, S.; Ma, Z.; Wei, Y. Effect of polyoxymethylene dimethyl ethers addition on spray and atomization characteristics using a common rail diesel injection system. *Fuel* **2016**, *186*, 235–247. [\[CrossRef\]](#)

22. Ma, Y.; Cui, L.; Ma, X.; Wang, J. Optical study on spray combustion characteristics of pode/diesel blends in different ambient conditions. *Fuel* **2020**, *272*, 117691. [\[CrossRef\]](#)
23. Liu, H.; Wang, Z.; Li, B.; Wang, J.; He, X. Exploiting new combustion regime using multiple premixed compression ignition (MPCI) fueled with gasoline/diesel/PODE (GDP). *Fuel* **2016**, *186*, 639–647. [\[CrossRef\]](#)
24. Wang, Z.; Liu, H.; Ma, X.; Wang, J.; Shuai, S.; Reitz, R.D. Homogeneous charge compression ignition (HCCI) combustion of polyoxymethylene dimethyl ethers (PODE). *Fuel* **2016**, *183*, 206–213. [\[CrossRef\]](#)
25. Liu, H.; Wang, Z.; Wang, J.; He, X.; Zheng, Y.; Tang, Q.; Wang, J. Performance, combustion and emission characteristics of a diesel engine fueled with polyoxymethylene dimethyl ethers (PODE3-4)/diesel blends. *Energy* **2015**, *88*, 793–800. [\[CrossRef\]](#)
26. Zhu, Y.; Lin, D.; Wei, X.; Zhang, W. Effect of PODE on Combustion and Emission Characteristics of a Turbo-Charged Intercooled Diesel Engine. *J. Shanghai Jiaotong Univ.* **2017**, *51*, 33–39.
27. Liu, J.; Sun, P.; Huang, H.; Meng, J.; Yao, X. Experimental investigation on performance, combustion and emission characteristics of a common-rail diesel engine fueled with polyoxymethylene dimethyl ethers-diesel blends. *Appl. Energy* **2017**, *202*, 527–536. [\[CrossRef\]](#)
28. Liu, H.; Wang, X.; Wu, Y.; Zhang, X.; Jin, C.; Zheng, Z. Effect of diesel/pode/ethanol blends on combustion and emissions of a heavy duty diesel engine. *Fuel* **2019**, *257*, 116064.1–116064.11. [\[CrossRef\]](#)
29. Li, X.; Jiang, B.; Xie, F.X.; Hong, W. Effects of injection parameters on combustion and emissions of diesel engine. *Trans. Csice* **2012**, *30*, 22–28.
30. Zhang, Z.; Liu, X.; Liu, H.; Wu, Y.; Yao, M. Effect of soybean oil/pode/ethanol blends on combustion and emissions on a heavy-duty diesel engine. *Fuel* **2020**, *288*, 119625. [\[CrossRef\]](#)
31. Wang, T.; Liu, J.; Sun, P.; Ji, Q.; Yang, C. Influence of injection parameters on combustion, gaseous emissions and particle size distribution of a CRDI diesel engine operating with PODE/diesel blends. *Fuel* **2020**, *281*, 118733. [\[CrossRef\]](#)
32. Hottel, H.C.; Broughton, F. Determination of true temperature and total radiation from luminous gas flames. *Ind. Eng. Chem. Anal. Ed.* **1932**, *4*, 166–175. [\[CrossRef\]](#)
33. Zhao, H.; Ladommatos, N. Optical diagnostics for soot and temperature measurement in diesel engines. *Prog. Energy Combust. Sci.* **1998**, *24*, 221–255. [\[CrossRef\]](#)
34. Zhang, J.; Jing, W.; Roberts, W.L.; Fang, T. Soot temperature and KL factor for biodiesel and diesel spray combustion in a constant volume combustion chamber. *Appl. Energy* **2013**, *107*, 52–65. [\[CrossRef\]](#)
35. Jing, W.; Roberts, W.; Fang, T. Comparison of Soot Formation for Diesel and Jet-A in a Constant Volume Combustion Chamber Using Two-Color Pyrometry. *SAE Tech. Pap.* **2014**. [\[CrossRef\]](#)
36. López, J.J.; Martín, J.; García, A.; Villalta, D.; Warey, A. Implementation of two color method to investigate late cycle soot oxidation process in a CI engine under low load conditions. *Appl. Therm. Eng.* **2017**, *113*, 878–890. [\[CrossRef\]](#)
37. Krieger, R.B. *The Computation of Apparent Heat Release for Internal Combustion Engines*; ASME Paper (NO. 66-WA/DGP-4); ASME: New York, NY, USA, 1966.
38. Reyes, J.G.; Quiros, E. Determination of the Start and End of Combustion in a Direct Injection Diesel Engine Using the Apparent Heat Release Rate. In *ASME Power Conference*; ASME: New York, NY, USA, 2017.
39. Li, B.; Yoo, K.H.; Wang, Z.; Boehman, A.L.; Wang, J. Experimental and numerical study on autoignition characteristics of the gasoline/diesel/ethanol and gasoline/diesel/pode/ethanol fuels. *Energy Fuels* **2019**, *33*, 11841–11849. [\[CrossRef\]](#)
40. Qi, J.; Hu, Y.; Niu, J.; Ma, W.; Jiang, S.; Wang, Y.; Jiang, Y. Evaluation of polyoxymethylene dimethyl ethers as a new type of diesel additives. *Fuel* **2018**, *234*, 135–141. [\[CrossRef\]](#)
41. Chen, H.; Su, X.; He, J.; Zhang, P.; Xu, H.; Zhou, C. Investigation on combustion characteristics of cyclopentanol/diesel fuel blends in an optical engine. *Renew. Energy* **2021**, *167*, 811–829. [\[CrossRef\]](#)
42. Geng, L.; Xiao, Y.; Li, S.; Chen, H.; Chen, X. Effects of injection timing and rail pressure on particulate size-number distribution of a common rail DI engine fueled with fischer-tropsch diesel synthesized from coal. *J. Energy Inst.* **2021**, *95*, 219–230. [\[CrossRef\]](#)
43. Quoc, H.X.; Vignon, J.; Brun, M. A New Approach of the Two-Color Method for Determining Local Instantaneous Soot Concentration and Temperature in a D.I. Diesel Combustion Chamber. *IEEE Trans. Instrum. Meas.* **1991**, *100*, 1368–1377.
44. Espey, C. Diesel Engine Combustion Studies in a Newly Designed Optical-Access Engine Using High-Speed Visualization and 2-D Laser Imaging. *SAE Tech. Pap.* **1993**. [\[CrossRef\]](#)
45. Arcoumanis, C.; Bae, C.; Nagwaney, A. Effect of EGR on Combustion Development in a 1.9L DI Diesel Optical Engine. *SAE Tech. Pap.* **1995**. [\[CrossRef\]](#)
46. Liu, J.; Wu, P.; Sun, P.; Ji, Q.; Zhang, Q.; Wang, P. Effects of iron-based fuel borne catalyst addition on combustion, in-cylinder soot distribution and exhaust emission characteristics in a common-rail diesel engine. *Fuel* **2021**, *290*, 120096. [\[CrossRef\]](#)