

Article

Effects of Two Pilot Injection on Combustion and Emissions in a PCCI Diesel Engine

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Abstract: The effects of two pilot injections on combustion and emissions were evaluated in a single-cylinder turbocharged diesel engine, which operated in premixed charge compression ignition (PCCI) modes with multiple injections and heavy exhaust gas recirculation under the low load by experiments and simulation. It was revealed that with the delay of the start of the first pilot injection ($SOI-P1$) or the advance of the start of second pilot injection ($SOI-P2$), respectively, the pressure, heat release rate (HRR), and temperature peak were all increased. Analysis of the combustion process indicates that, during the two pilot injection periods, the ignition timing was mainly determined by the $SOI-P2$ while the first released heat peak was influenced by $SOI-P1$. With the delay of $SOI-P1$ or the advance of $SOI-P2$, nitrogen oxide (NO_x) generation increased significantly while soot generation varied a little. In addition, increasing $Q1$ and decreasing the second pilot injection quantity ($Q2$) can manipulate the NO_x and soot at a low level. The advance in $SOI-P2$ of 5 °CA couple with increasing $Q1$ and reducing $Q2$ was proposed, which can mitigate the compromise between emissions and thermal efficiency under the low load in the present PCCI mode.

Keywords: premixed charge compression ignition (PCCI); multiple injection; two pilot injection; combustion; emissions; experiments; numerical simulation



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1. Introduction

With increasing concerns about fossil fuel consumption, environmental protection, and stricter emission regulations, the production of engines urgently needs higher fuel conversion efficiency and lower emissions. Diesel engines are widely used in industry and traffic due to the advantages such like high heat efficiency and low fuel consumption. Nevertheless, high nitrogen oxides (NO_x) and soot emissions have been the most prominent problem in diesel engines, so the newly developed diesel engine should have lower soot and NO_x emissions when maintaining high thermal efficiency. Another challenge is the difficulty in simultaneously reducing the two types of emission, for which there is a trade-off [1,2].

At present, the main measures taken include multi-stage injection, high injection pressure, micro injector orifices, and new clean alternative fuels. Fraioli et al. [3] evaluated the feasibility of applying methane-diesel dual-fuel to a light-duty engine using one-stage and two-stage injection strategies under medium and high engine load, and found that simulated predicted values are reasonably consistent with experimental values. Mueller et al. [4] put forward the concept of ducted fuel injection for a direct injection engine, which is an effective approach for mitigating the compromise between harmful pollutants and thermal efficiency. Homogeneous charge compressed ignition (HCCI) combustion has been widely researched in order to reduce soot and NO_x emissions and improve the thermal efficiency. However, its combustion rate and combustion phase are difficult to control, and the diluted

mixing characteristics lead to a narrow operating range [5–7]. Different from the complete homogeneous charge in HCCI modes, premixed charge compression ignition (PCCI) operates with larger proportions of premixed charge than traditional model, and in the meantime it deploys multiple injection strategies and exhaust gas recirculation (EGR) rates to greatly increase the controllability of combustion rate [8,9]. The effect of EGR in a diesel engine adopting the PCCI mode has been discussed by Jain et al. [10]. It was reported that a satisfactory two-stage injection timing coupled with an appropriate EGR rate can achieve a good compromise in improving engine performance and reducing emissions. Lu et al. [11] also found that EGR coupled with multi-stage injection can simultaneously reduce soot and NO_x emissions. Regarding multi-stage injection strategies, after the comparison between the single and two stage injections, Yu et al. [12] discovered a better effect on combustion and emission characteristics which can be achieved by using two-stage injection strategies. A similar conclusion was obtained in the work of Park et al. [13], in which they adopted one-stage and two-stage injection strategies to reduce HC and CO emissions in a PCCI diesel engine. Cao et al. [14] demonstrated that in a two-stage injection strategy, the second injection flame propagated faster, and the soot concentration was more evenly distributed. On the side, the impacts of the injection parameters on fuel combustion have also been investigated. Yin et al. [15] found that, in comparison to one-stage injection strategy, the two-stage injection strategy with suitable injection parameters can cut emissions. He et al. [16] reported that the emissions of soot and NO_x simultaneously decreased with the advance of the pilot injection timing. Fajri et al. [17] concluded that prolonging the combustion duration had a positive effect on the combustion process and the reduction of NO_x emissions. Hence, the combination of an appropriate multi-stage injection strategy and EGR can play a significant part in lessening soot and NO_x emissions in PCCI combustion mode [18–20]. Besides, the gasoline fuel also can be an available solution for the next emissions legislation targets since the pollutant emissions will be reduced drastically, and the partially premixed combustion process employing gasoline blend can allow us to reduce soot and NO_x emissions and improve the thermal efficiency [21].

A variety of fuel injection strategies such as pilot-main injection, main-post injection, and pilot-main-post injection has been adopted to explore the impacts of injection strategies on performance and harmful pollutants [22–24]. However, the pilot-pilot-main injection strategy has been less put into effects. In addition, compared with the high load, the lower fuel amount can lead to the low local concentration and incomplete combustion of fuel-air mixtures in the cylinder, and the increase of NO and soot emissions under the low load in normal PCCI mode [25]. Hence, in the present study, the authors studied the combustion process, NO, and soot generation using pilot-pilot-main injection strategy under the high EGR rate of 44% and low IMEP of 0.44 MPa at 1900 rpm through experiments to broaden the load range of PCCI mode. Moreover, to further mitigate the compromise between harmful pollutants and thermal efficiency, the timing and proportion of the two pilot injections were adjusted through simulation software to probe into the performance and harmful pollutants characteristics of the PCCI mode.

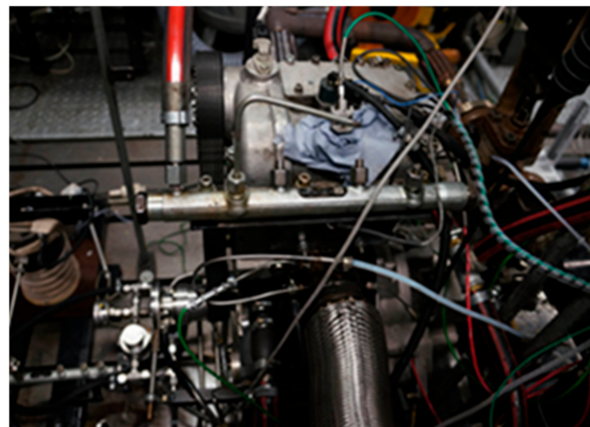
2. Methodology

2.1. Experimental Facility

The experiment was brought into operation on a high-pressure common-rail single-cylinder diesel engine originating from the 4-cylinder Daimler OM646 diesel engine. The detailed test prototype parameters are shown in Table 1, and the experimental facility is presented in Figure 1. In order to meet the European V and stricter emission standards, the high-pressure common-rail system was equipped to flexibly dominate the number of injections and the injection pulse width. The indicated mean effective pressure (IMEP) was used to assess engine performance. A heavy EGR rate of 44% was coupled with the intake supercharging to achieve the diesel PCCI combustion mode.

Table 1. Specifications of the actual engine.

Make and Model	Direct Injection
Number of nozzle orifices	7
Spray angle (°)	153
Injector	Bosch CRI-2.2
Rated speed (rpm)	4000
Compression ratio	15.88
Displacement (L)	0.537
Piston stroke (mm)	88.34
Cylinder bore (mm)	88

**Figure 1.** Test bench.

The main test equipment is displayed in Table 2. The in-cylinder pressure was ascertained by a pressure sensor (Model 6043ASP, Germany). The engine crank angle was recorded by an encoder. The heat release attributes were obtained by using a combustion analyzer IndiCom software. NO_x and soot emissions were measured by a chemiluminescence analyzer and an AVL439 optical Hartridge opacimeter, respectively.

Table 2. Main equipment for engine testing.

Instrumentation	Manufacturer	Type
Fuel mass flow meter	Siemens AG	1GG6164
Air mass flow meter	ABB	Sensyflow
Piezoelectric sensor	Kistler	6043ASP
Combustion analyzer	AVL List GmbH	IndiCom
Gas analyzer	HORIBA	7170DEGR
Opacimeter	AVL	415 SE

At the mode of the IMEP of 0.44 MPa at 1900 rpm, the parameters of the fuel supply system are shown in Figure 2. Figure 2 indicates the opening timing of the solenoid valve and injection pulse width under the fuel injection, in which the three pulses of solenoid valve are two pilot injection and main injection.

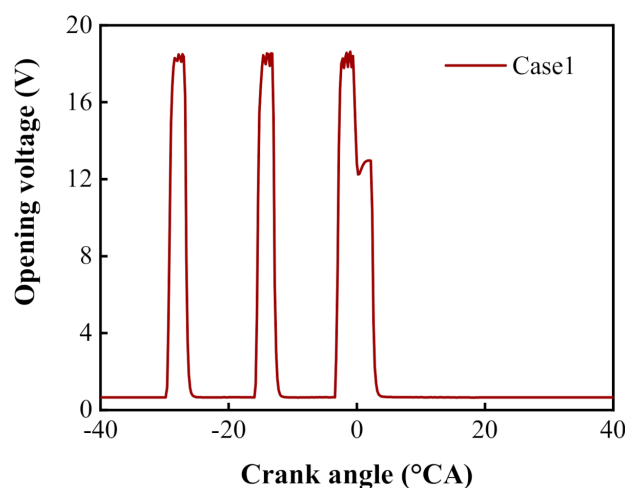


Figure 2. Injection pulse.

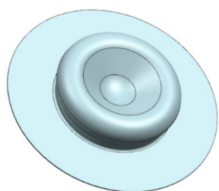
2.2. Modeling

The Pressure-Implicit with Splitting of Operators (PISO) algorithm was implemented by the AVL Fire software to simulate the pressure-velocity coupling process [26]. In order to accurately describe the physical and chemical changes of working medium in a real PCCI diesel engine [27], the sub-models, including turbulence [28], spray impingement [29], combustion [30], and emission [31] models were adopted, which are shown in Table 3.

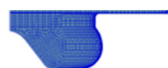
Table 3. Sub-models.

Models	Definition
Turbulence	k–zeta–f
Atomization/breakup mode	Dukowicz/WAVE
Combustion	ECFM–3Z
Spray impingement	Walljet1
Nitrogen oxide (NO _x) formation	Extended Zeldovich
Soot formation	Kinetic

The piston bowl profile is shown in Figure 3a. Since the diesel injector used in the research has seven equally distributed orifices, the calculation was carried out using a seventh of the combustion chamber. The computational grids applied in this study were composed of approximately 21,840 and 17,840 cells, respectively, as shown in Figure 3b,c. The simulation was implemented with a bounded system, from the intake valve closing at 122 °CA to the exhaust valve opening at 116 °CA.

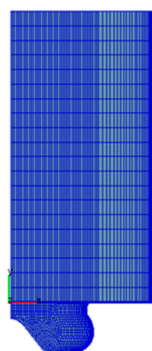


(a) Piston bowl profile.



(b) Bottom dead center (BDC).

Figure 3. Cont.



(c) Top dead center (TDC).

Figure 3. Simulation model: (a) piston bowl profile; (b) bottom dead center (BDC); (c) calculation grids.

The initial calculation conditions and boundary parameters are shown in Table 4, among which the simulated initial temperature, initial pressure, initial fuel temperature, and EGR were obtained based on experiments. The opposite cut surface of the sector was used as the cycle boundary. The cylinder wall, cylinder head, and the top of the combustion chamber were used as fixed wall surfaces. The initial temperatures around chambers were endowed with experienced data.

Table 4. The boundary conditions of calculation.

Item	Value
Piston top temperature (K)	596
Cylinder head temperature (K)	557
Cylinder wall temperature (K)	407
Initial fuel temperature (K)	320
Exhaust gas recirculation (EGR) (%)	44
Initial temperature (K)	367
Initial pressure (MPa)	0.135

2.3. Operating Methodology and Model Validation

Fuel injection schemes are shown in Table 5. Based on Case1, Case2 tunes the first and second pilot injection timings, and Case1-1 and Case1-2 change the fuel mass of the two pilot injection. Case1-3 adjusts the fuel amount and the second pilot injection timing of the two pilot injection simultaneously.

Table 5. Injection timing for various injection schemes.

Injection Scheme	SOI-P1 (°CA)	SOI-P2 (°CA)	SOI-M (°CA)	QM (mg)	Q1 (mg)	Q2 (mg)
Case1	−33	−19	−6	8.26	1.84	1.84
Case2	−38/−33/−28	−19	−6	8.26	1.84	1.84
Case3	−33	−24/−19/−14	−6	8.26	1.84	1.84
Case1-1	−33	−19	−6	8.26	2.94	0.74
Case1-2	−33	−19	−6	8.26	0.74	2.94
Case1-3	−33	−24	−6	8.26	2.94	0.74

The simulation model established in this article was verified at experimentally operation model at 0.44 MPa, of which the specific parameters are presented in Table 6. Figure 4 manifests the validation of the simulated and experimental values of cylinder pressure, heat release rate (HRR), NO, and soot. It seems that the profile of simulated cylinder pressure, HRR, NO, and soot processed well with the experimental one, only having a little larger outbreak pressure. It can be explained as, in a real engine operation, there were

more practical losses. The error between the simulated pressure and measured one was found to be basically less than 5%, which indicates the simulation model can be used for the research schemes of various pilot injection parameters.

Table 6. Injection parameters for a real operation mode.

Injection Scheme	SOI-P1 (°CA)	SOI-P2 (°CA)	SOI-M (°CA)	QM (mg)	Q1 (mg)	Q2 (mg)
Pmi = 0.44 MPa	−30	−16	−3	8.31	1.84	1.84
	−33	−19	−6	8.26	1.84	1.84
	−36	−22	−9	8.12	1.84	1.84

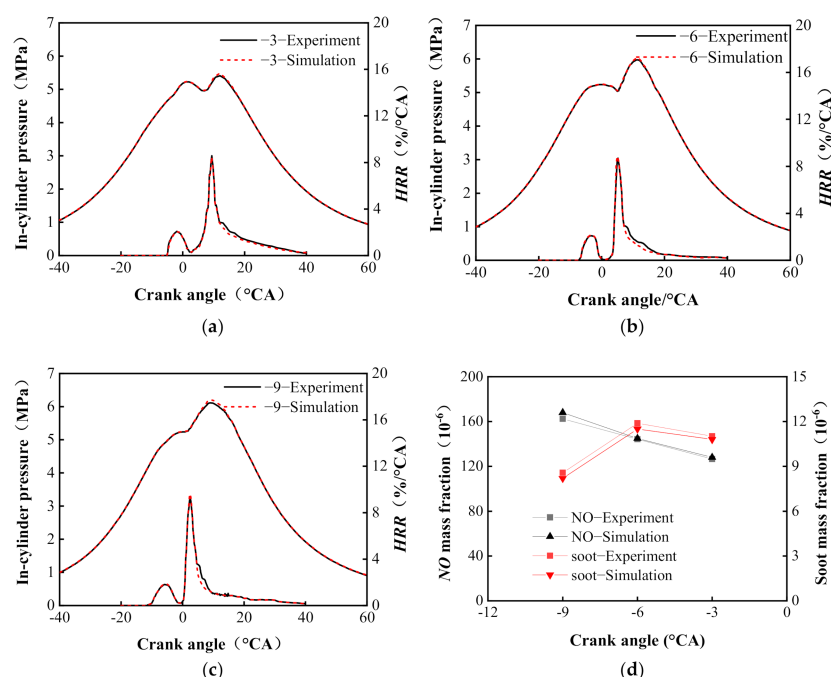


Figure 4. Validation of the simulated and experimental values of cylinder pressure, heat release rate (HRR), NO, and soot: (a) SOI-M = −3 °CA; (b) SOI-M = −6 °CA; (c) SOI-M = −9 °CA; (d) NO and soot.

3. Results

3.1. Effects of Pilot Injection Timing

3.1.1. Characteristic of Heat Release

The pressure and HRR at diverse SOI-P1 schemes and SOI-P2 schemes are, respectively, shown in Figure 5, in which the experimental data have been indicated. It can be easily found that the second peak pressure and maximum HRR increased with delaying SOI-P1. Generally, after the first pilot fuel was injected into the cylinder, it was difficult to form the ignition area due to factors such as insufficient fuel amount, fuel-air diffusion, and lower temperature. Hence, the ignition and the spread of flame take place after the second pilot injection [32]. With the delay of SOI-P1, a favorable atmosphere of high pressure, high temperature, and strong turbulent was developed in cylinder, which made the first pilot fuel mix well with air to form combustible mixtures. The combustible mixtures formed by the first pilot fuel and the second pilot fuel were automatically ignited under appropriate conditions and released more heat. Hence, the increase in heat release from pilot fuel made the temperature and pressure rise significantly before the main injection. In addition, more combustible mixtures can be formed after the main injection fuel, enhancing the combustion temperature. Owing to the combined heat released by the pilot fuel and main injection, the energy forming the main injection fuel and air mixtures was enhanced.

Therefore, the mixing rate was increased, which resulted in an acceleration in heat release and the advance in main combustion.

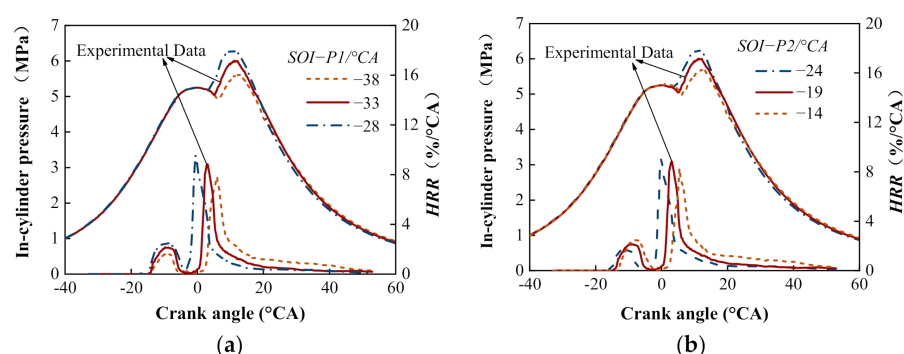


Figure 5. Pressure and HRR: (a) adaptation of *SOI-P1*; (b) adaptation of *SOI-P2*.

With the advance *SOI-P2*, the pressure peak and maximum HRR gradually increased, and the phase advanced smoothly. The second pilot fuel injection earlier with advancing *SOI-P2* brought about the advance of the pilot fuel ignition timing. Simultaneously, more incompletely burnt mixtures formed by the pilot fuel participated in the subsequent main combustion. The former heat release coupled the main combustion, which enhanced the turbulences and accelerated the heat release of the main combustion.

The bulk gas temperature in cylinder for different *SOI-P1* schemes and *SOI-P2* schemes are presented in Figure 6. More pilot fuel was involved in burning the combustion in time due to the postponed *SOI-P1*, which intensified the formation of the fuel-air mixture and accelerated the heat released from the main combustion. As a result, with the delay of *SOI-P1*, the bulk gas temperature rose accordingly, and the differences in the maximum combustion temperature reached 100 K. Conversely, the bulk gas temperature peak gradually dropped with delaying the *SOI-P2*. With the remaining *SOI-P1* unchanged and delaying *SOI-P2*, the ignition timing of the pilot fuel was postponed, which resulted in more pilot fuel burning in the initial stage. Consequently, the heat release in the main combustion slowed down and the combustion duration was prolonged, resulting in further significant low-temperature combustion effects. The maximum temperature was dropped by 80 K in Case3, with the delay of *SOI-P2*.

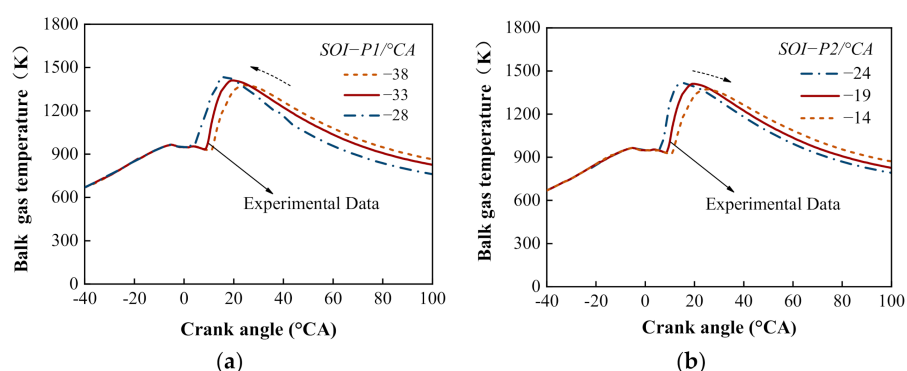


Figure 6. Bulk gas temperature in cylinder: (a) adaptation of *SOI-P1*; (b) adaptation of *SOI-P2*.

3.1.2. Combustion Features at Particular Moments

Figure 7 displays the temperature, fuel-air equivalence ratio, *NO*, and soot graphs for diverse *SOI-P1* schemes of Case2. Only the combustion features for different *SOI-P1* schemes are shown in this paper since the combustion features for different *SOI-P1* schemes and *SOI-P2* schemes are similar. Analysis are focused on three typical heat release timings, namely CA10, CA50, and CA90 (Appendix A). In the initial combustion, for the *SOI-P1* of -38°CA and -33°CA , a small amount of *NO* was generated because

the high temperature and equivalence ratio zones were mainly concentrated in the bottom of the combustion chamber. However, for the $SOI-P1$ of -28°CA , more NO was generated due to the more high-temperature zones formed at the edge of rich mixtures. At the CA50 moment or later, the mixtures diffused quickly with the assistance of the squeezed flows. In addition, the temperature rose rapidly with the ongoing combustion at areas of suitable fuel-air equivalence ratio. NO generation corresponded well to those scorching areas with proper lean mixtures. With the advance of $SOI-P1$, the generation of NO reached its minimum at the $SOI-P1$ of -38°CA , which was caused by the low reaction temperature as a whole. In general, the proper advance of $SOI-P1$ was beneficial for the NO reduction.

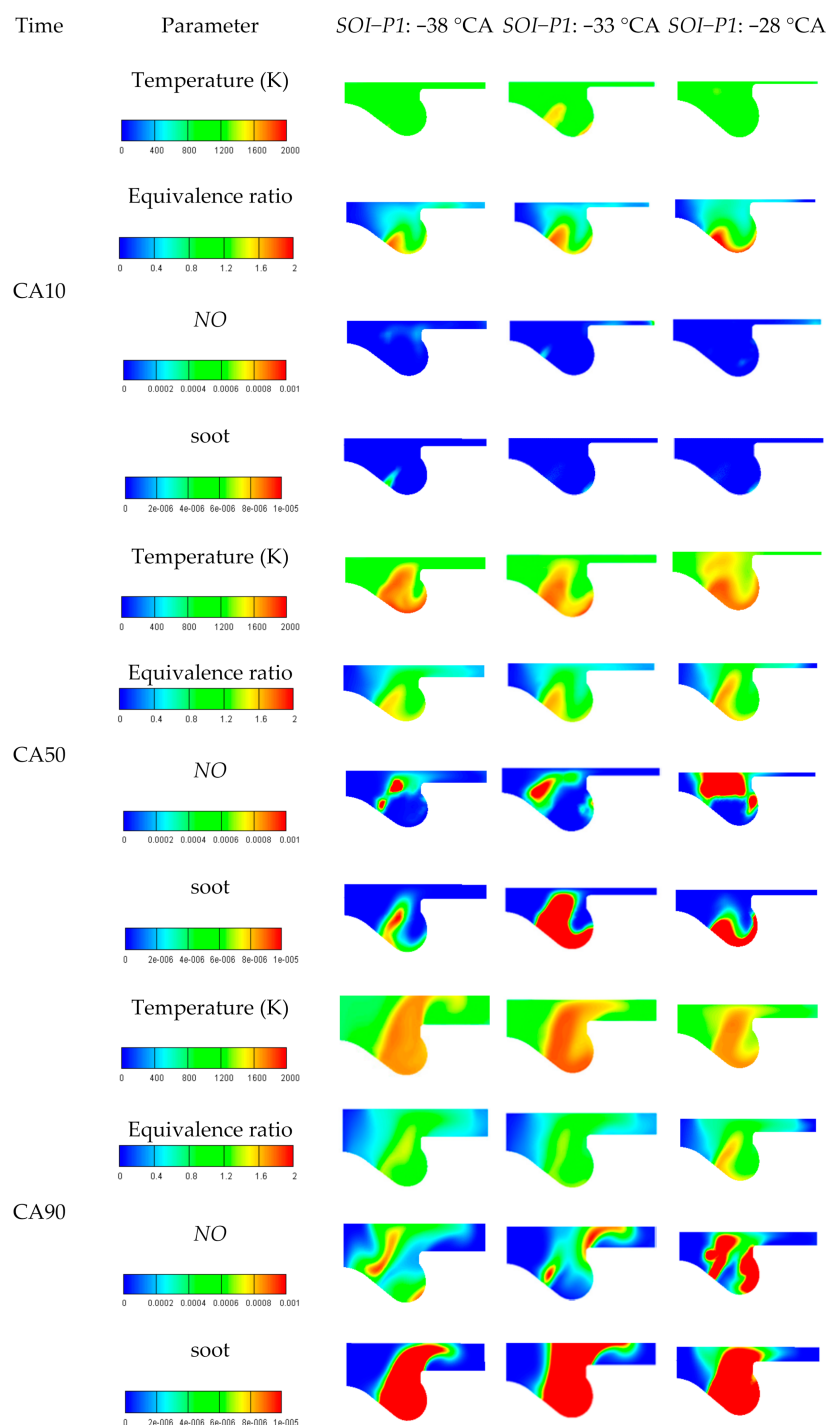


Figure 7. Temperature, fuel-air equivalence ratio, NO , and soot graphs for diverse $SOI-P1$ schemes in Case2.

The soot generation regions appeared fine accordance with the fuel-air equivalence ratio. Firstly, soot was generated near the combustion chamber wall. This can be attributed to the relatively higher fuel-air equivalence ratio and the nethermore balk gas temperature. At the CA50 moment, the generation of soot was concentrated near the cylinder wall and in the concave with high fuel-air equivalence ratio. Working volume expanded continuously with the proceeding of combustion, which resulted in the rapid diffusion of mixtures. Thus, the mixtures became lean. The flame gradually diffused to the whole chamber as the piston moved down, when the high-temperature zones coincided with the fuel concentration area, resulting in the increase of soot formation zones. With the advance of *SOI-P1*, the generation of soot slightly reduced under combined effects of the temperature and fuel-air mixtures. At the *SOI-P1* of -38°CA , the soot generation at CA50 and CA90 moments dropped to its minimum, compared with the other two schemes, respectively. It can be explained as the advance of *SOI-P1* led to a prolongation in the main combustion duration, the delay of the CA50 and CA90 moments and the enough large working volume, which was more suitable for fuel-air diffusion and combustion.

3.1.3. Emission Characteristics

The generation of *NO* and soot in cylinder for *SOI-P1* injection schemes are presented in Figure 8a. It was worth nothing that *NO* generation kept good agreement with the bulk gas temperature, as shown in Figure 6a. With the delay of *SOI-P1*, the generation of *NO* increased since more mixtures burnt at that moment and released a large amount of heat, which led the bulk gas temperature rise. The multiple injections made the fuel and air mix better, which beneficially repressed the generation of soot. Generally, the terminal soot was deeply dependent on not only the distribution of fuel-air equivalence ratio, but also the bulk gas temperature. As shown in Figure 6b, delaying *SOI-P1* increased the maximum combustion temperature which promoted the oxidation of soot, however, it also decreased the post combustion temperature rapidly which restrained the oxidation of soot slightly. On the whole, the final soot was increased with the delay of *SOI-P1*.

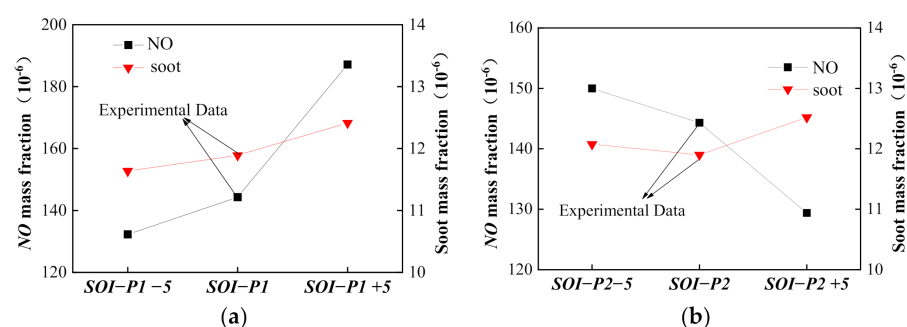


Figure 8. The generation of *NO* and soot in the cylinder: (a) adaptation of *SOI-P1*; (b) adaptation of *SOI-P2*.

Figure 8b depicts the generation of *NO* and soot in cylinder for the *SOI-P2* injection schemes. The generation of *NO* was generally determined by the bulk gas temperature and oxygen concentration in the reaction area. With the delay of *SOI-P2*, the generation of *NO* was reduced. At different injection schemes, the generation of *NO* coincided conformably to the temperature with referring to Figure 6, which indicates that the temperature had a decisive impact on the generation of *NO*. Advancing *SOI-P2* raised the reaction temperature, which reinforced the soot oxidation rate, and shortened the combustion duration, which impaired the diffusion and mixing of fuel with air. Owing to these two aspects, there was only a little change in the final soot generation.

3.2. Effect of Two Pilot Injection Proportions

3.2.1. Characteristic of Heat Release

The cylinder pressure and *HRR* at diverse pilot injection ratio schemes are, respectively, shown in Figure 9a, which contains experimental data. Increasing Q_1 and decreasing Q_2 , the first peak of cylinder pressure and *HRR* increased, while the primary peak declined. On the one hand, more mixtures formed by the pilot fuel burnt and released heat in the initial combustion, raising the first peak of cylinder pressure. On the other hand, the countering unburnt mixtures were reduced, which decreased the mixing rate of fuel with air, the burst pressure and *HRR* in the main injection. In contrast, the pressure and *HRR* of the main combustion increased and the heat release phase advanced in Case1-2. It can be explained as the unburnt mixtures mainly stemmed from the second pilot fuel combined with the main combustion since Q_2 was greater than Q_1 , which brought about more intense turbulences and accelerated the mixing rate of fuel with air as well. Compared with Case1-1, the main pressure peak rose in Case1-3. This was due to the fact that more pilot fuel participated in the main combustion when ahead of $SOI-P_2$, resulting in faster main heat release. Similarly, more unburnt mixtures originated from the pilot fuel participated in the subsequent main combustion, leading to an increase in the main heat release peak.

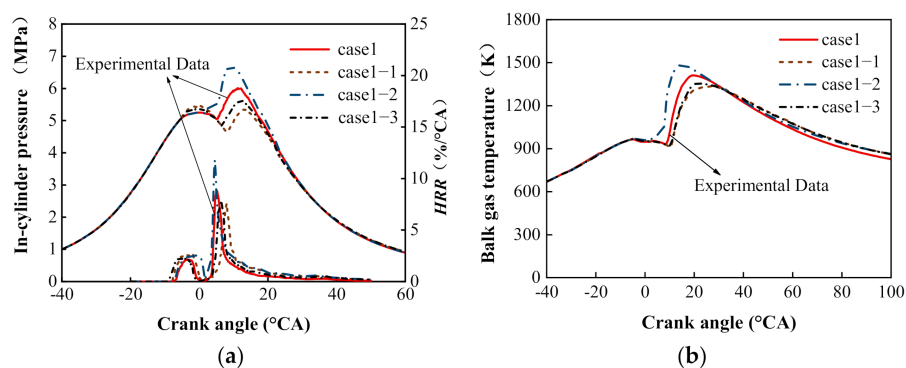


Figure 9. Characteristic of heat release: (a) pressure and *HRR*; (b) bulk gas temperature.

The temperature decreased, and the phase was delayed with the reduction of Q_2 , as shown in Figure 9b. At the initial combustion, when the pilot injection proportion was 1:4, the bulk gas temperature rose rapidly because of the greater *HRR*. Although a greater Q_1 was more favorable to fulfilling low-temperature combustion, the thermal efficiency was reluctantly reduced. Hence, coupled with increasing Q_1 and reducing Q_2 , the scheme of advancing $SOI-P_2$ was adopted in Case1-3 to remedy this issue.

3.2.2. Combustion Features at Particular Moments

Temperature, fuel-air equivalence ratio, *NO*, and soot emissions graphs for diverse pilot injection ratio schemes are displayed in Figure 10. Analysis is focused on three typical heat release timings, namely CA10, CA50, and CA90. From the detailed combustion proceeding with the heat release timing of CA10, marginally fuel-air mixtures accumulated at the bottom of the concave. At this moment, high temperature zones also emerged in the local area of the concave wall with rich mixtures. With reference to emissions, a little *NO* emission was generated, which was mainly diffused at the bottom of the concave and in the wall zone of high temperature. Tiny soot was generated at the bottom of the concave only in Case1 because of its high local temperature. Compared with the CA10 moment, the first pilot injection proportion increased at the CA50 moment, which brought about the relatively light color on the temperature and the fuel concentration area. This demonstrated the relatively low local temperature and lean mixture zones at the CA50 moment. It was worth mentioning that *NO* emission was mainly distributed in the areas with high temperature and low equivalence ratio. Thus, *NO* generation lessened since the rise of the first pilot injection proportion. However, in Case1-3, partial *NO* concentration

zones increased slightly with a growing tendency in the first pilot injection proportion and the advance of $SOI-P2$. At the CA90 moment, the cylinder volume increased quickly. Correspondingly, mixtures diffused speedily and thus the fuel-rich area reduced, which resulted in the improvement on the mixture uniformity and even the quick spread of flame spread to the whole concave. With the increase of high-temperature regions, NO gradually diffused to the middle and upper concave, and the zone near the concave wall with a small amount of fuel-air mixtures. NO generation dropped with the increase of first pilot injection proportion. Soot generation was in agreement with the distribution of the high temperature and fuel-rich zones.

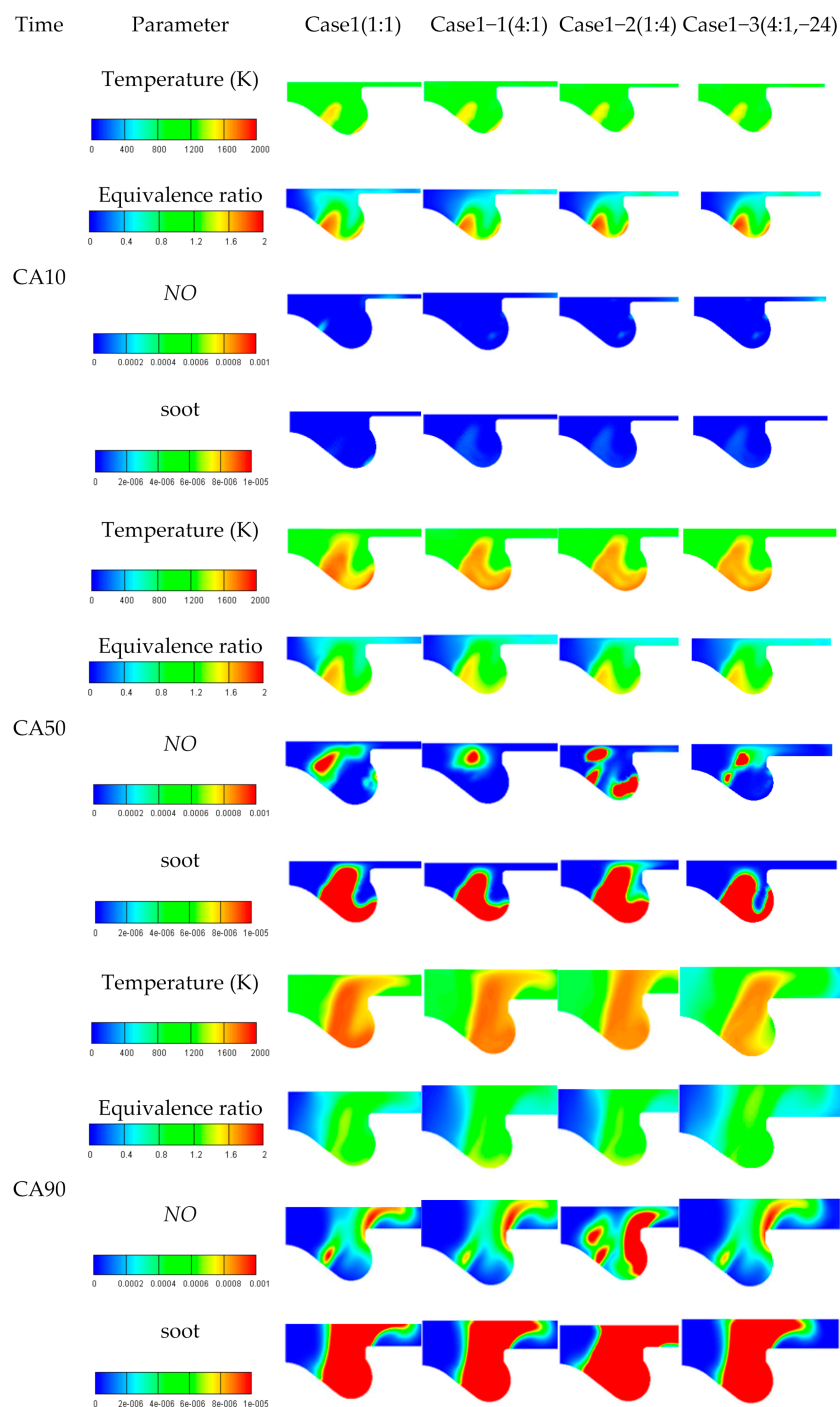


Figure 10. Temperature, fuel-air equivalence ratio, NO , and soot graphs for diverse pilot injection ratio schemes.

3.2.3. Emission Characteristics

The NO and soot mass fraction profile for diverse pilot injection ratio schemes are shown in Figure 11. Figure 11a demonstrates that NO generation, which was controlled by the bulk gas temperature, increased, and its phase advanced with the increase of $Q2$. Generally speaking, increasing $Q2$ was analogous to the function of advancing the main injection or increasing the main fuel injection. Thus, compared with Case1, heat release was more focused and its phase was near the top dead center (TDC) in Case1-2, which brought about the high temperature and the increase of NO generation. In addition, with the increase of $Q2$, a lot of fuel cannot burn adequately before the main injection began. Hence, large amounts of fuel in the main injection were injected into the pilot combustion area, and it didn't mix well with air under the high temperature and anoxic condition, leading to a rise in soot generation. Compared with Case1, increasing $Q1$ lessened the generation of NO and soot, but it was not conducive to the thermal efficiency in Case1-1. In consequence, on the basis of increasing $Q1$ and reducing $Q2$, the scheme of advancing $SOI-P2$ was proposed in Case1-3, which reduced the emission of NO and soot and improved the combustion process in cylinder referring to Figures 9 and 10.

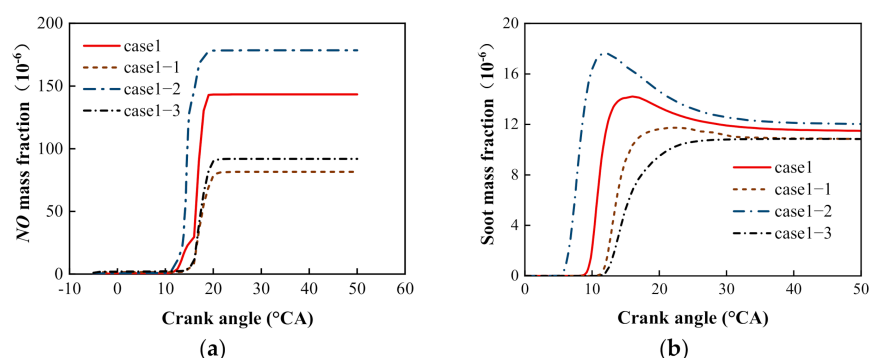


Figure 11. Emission characteristics for diverse pilot injection ratio schemes: (a) NO ; (b) soot.

4. Discussion

Compared with the high load, the lower fuel amount can lead to the low local concentration and incomplete combustion of fuel-air mixtures in the cylinder, and the increase of NO and soot emissions under the low load in normal PCCI mode. Hence, the effects of two pilot injection timings and injection ratios on the emission and combustion using pilot-pilot-main injection strategy under the high EGR rate of 44% and low IMEP of 0.44 MPa at 1900 rpm were researched by experiments and simulation to broaden the load range of the present PCCI mode, and the following conclusions were gained.

With remaining $SOI-P2$ unchanged and advancing $SOI-P1$, the heat release in the two pilot injection periods decreased. With remaining $SOI-P1$ unchanged, the ignition took place early with advancing $SOI-P2$. The in-cylinder pressure, HRR and temperature peak decreased and their corresponding phases were postponed with the advance of $SOI-P1$, which was contrary to that of advancing $SOI-P2$. In addition, with the advance of $SOI-P1$ or $SOI-P2$, respectively, NO emissions presented fine accordance with the temperature peak, while the soot generation regions were consistent with the fuel-air equivalence outline.

Increasing $Q1$ and reducing $Q2$ can effectively restrain the generation of NO and soot. However, the pressure, HRR , and combustion temperature peak were all decreased. It can be found from the foregoing analysis that the pressure, HRR , and combustion temperature peak were all increased with the advance of $SOI-P2$. Hence, the advance in $SOI-P2$ of 5 °CA coupled with increasing $Q1$ and reducing $Q2$ was proposed in Case1-3, which can improve the thermal efficiency while maintaining little change in emissions under the low load in the present PCCI mode. In summary, effects of adjusting two pilot injection timings and proportions simultaneously in Case1-3 on combustion were evaluated based

on simulation works, which can provide valuable references for mitigating the compromise between emissions and thermal efficiency under the low load in the present PCCI mode.

5. Conclusions

A scheme of the advance in $SOI-P2$ of $5^\circ CA$ coupled with increasing $Q1$ and reducing $Q2$ was proposed in Case1-3, which can improve the thermal efficiency while maintaining little change in emissions under the low load in the present PCCI mode. Future research activities will be focused on the effects of using new clean alternative fuels, such as dimethyl carbonate (DMC) and biodiesel, as blending components with diesel, respectively, on combustion and emissions in the PCCI diesel engine, in order to further reduce emissions and meet the next emissions legislation targets.

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Appendix A

Table A1. The abbreviations used in this manuscript.

QM	Main injection quantity
TDC	Top dead center
BDC	Bottom dead center
CA10	When the accumulated HRR attained ten percent of the total HRR
CA50	When the accumulated HRR attained fifty percent of the total HRR
CA90	When the accumulated HRR attained ninety percent of the total HRR
HRR	Heat release rate

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