Experimental Study on High-Load Extension of PODE/Gasoline Dual-Fuel RCCI (Postprint)

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Abstract

A novel oxygenated fuel PODE was adopted as the in-cylinder direct injection fuel to achieve PODE/gasoline dual-fuel RCCI combustion. The effects of PODE on RCCI dual-fuel combustion and emissions under different boundary conditions were studied, and high-load extension experiments were conducted incorporating a late intake valve closing strategy. The results show that, compared with diesel fuel, PODE as a direct injection fuel can achieve lower soot emissions while effectively improving combustion efficiency and thermal efficiency; reducing λ can effectively suppress the peak combustion rate, while the soot emissions of PODE/gasoline RCCI are insensitive to λ, and extremely low soot emissions can still be achieved even under fuel-rich conditions with $\lambda < 1$, but the near-stoichiometric region can cause CO emission deterioration; late intake valve closing can reduce in-cylinder pressure and peak combustion rate, but excessively delayed intake valve closing timing leads to reduced intake air quantity, causing an increase in NOx; combining late intake valve closing with high boost to achieve stoichiometric combustion can extend the high-load range to 2.31 MPa IMEP, without causing significant deterioration in brake thermal efficiency.

Full Text

Preamble

Experimental Study on High-load Extension of PODE/Gasoline Dual-fuel RCCI Operation

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Abstract

Experimental investigations on high-load extension of PODE/gasoline RCCI operation were conducted in a single-cylinder heavy-duty diesel engine under different boundary conditions using a late intake valve closing (LIVC) strategy. The results show that compared to diesel, using PODE as direct injection fuel could achieve much lower smoke emissions with improved combustion efficiency and thermal efficiency. The smoke emissions of PODE/gasoline RCCI are not sensitive to λ, and ultra-low smoke could be achieved even under fuel-rich conditions, while reduced λ could suppress the peak heat release rate effectively. However, high CO is observed near stoichiometric operation. The LIVC strategy could reduce in-cylinder pressure and heat release rate. LIVC combined with intake boosting enables the upper load to extend to 2.31 MPa IMEP while maintaining relatively acceptable indicated thermal efficiency. However, too retarded LIVC timing would lead to increased NOx and deterioration of indicated thermal efficiency.

Keywords: PODE; dual-fuel; RCCI; LIVC; load extension

Introduction

Internal combustion engines serve as the dominant power source in national economic operations and represent the primary consumers of petroleum and sources of urban pollutant emissions [1,2]. As global ecological and environmental issues become increasingly severe and the energy crisis continues to intensify, countries worldwide, including China, have implemented increasingly stringent emission regulations for internal combustion engines. In particular, recent concerns regarding ecological problems caused by CO_2 emissions have demanded that the engine industry simultaneously achieve substantial reductions in harmful gas emissions while continuously improving thermal efficiency [3,4]. To meet the requirements of future ultra-low emission regulations and thermal efficiency improvement, numerous efficient and clean novel combustion modes have been proposed domestically and internationally in recent years, with in-depth exploration conducted in combustion optimization theory and control technology. Consequently, novel combustion technologies have gradually become a hot topic and frontier in the field of advanced internal combustion engine combustion theory and new combustion technology research [5-7].

The diesel/gasoline dual-fuel RCCI (Reactivity Controlled Compression Ignition) combustion mode achieves stratified control of reactivity and concentration through port injection of high-octane gasoline fuel and direct in-cylinder injection of high-cetane diesel fuel, where the diesel ignites near top dead center to initiate combustion of the high-octane homogeneous mixture. RCCI can modulate the overall reactivity of the in-cylinder charge by varying the injection proportion of the two fuels according to load-dependent reactivity requirements. Additionally, the direct injection strategy simultaneously creates local reactivity and concentration stratification, and coupling with appropriate EGR can effectively control ignition timing, combustion phasing, and reaction rates. Consequently, compared to novel combustion modes such as HCCI, RCCI effectively extends the high-load limit [8-10]. However, further expanding the high-load operating range and achieving efficient, clean combustion across the full load spectrum with diesel/gasoline RCCI remains challenging. Previous studies have shown [11] that as load increases, the gasoline port injection proportion typically needs to be raised to reduce the overall reactivity of the in-cylinder charge for combustion phasing control. However, it is essential to prevent the port-injected gasoline from auto-igniting before the direct-injected diesel ignites. Simultaneously, to enhance fuel reactivity and concentration stratification for combustion rate control at high loads, EGR introduction and port premixing injection quantities must be limited. As load continues to increase, the rise in direct-injected diesel quantity also leads to elevated soot emissions, while air-fuel ratio constraints impose higher demands on intake boosting capabilities for achieving even greater loads in RCCI. Thus, it is evident that diesel fuel is not the most ideal direct injection fuel for RCCI combustion mode.

PODE ($CH_3O(CH_2O)nCH_3$) is a novel diesel alternative fuel whose unique physicochemical properties (absence of C-C bonds, high oxygen content, and relatively high cetane number) can effectively reduce soot emissions from diesel engines [12-14]. However, due to its significantly lower volumetric heating value compared to diesel, longer injection duration is required for equivalent energy content, necessitating optimization of the fuel delivery system and injection strategy. This makes it difficult to apply directly in conventional diesel engines. For RCCI combustion mode, however, the direct injection proportion is relatively small, allowing conventional fuel systems to meet injection requirements. Moreover, the increased direct injection volume per unit heating value also facilitates in-cylinder mixture stratification and enables control of multiple injection strategies. Combined with longer injection durations, this helps strengthen control over ignition and combustion processes. Based on this rationale, the present study employs PODE as the direct injection fuel to conduct an exploratory investigation into the combustion and emission characteristics of PODE/gasoline dual-fuel RCCI and its potential for high-load extension.

1.1 Experimental Fuels and Setup

In this study, RON 95 commercial gasoline was used for port injection, while PODE with a cetane number of 75.5 served as the direct injection fuel. The physicochemical properties of gasoline and PODE are presented in Table 1 .

The experiments were conducted on a six-cylinder turbocharged intercooled, electronically controlled high-pressure common rail diesel engine with a single-cylinder displacement of 1.08 L. The sixth cylinder was modified as the test cylinder with independent intake and exhaust systems as well as a dedicated fuel delivery system, while the remaining five cylinders remained unchanged. The basic specifications of the test engine are listed in Table 2 , and a schematic diagram of the engine test bench is shown in Figure 1 [Figure 1: see original paper]. To achieve in-cylinder mixing of the two fuels with different properties, PODE and gasoline employed two independent fuel injection systems. The PODE direct injection system was self-developed, enabling flexible control over injection frequency, timing, duration, and pressure. In this study, single injection of PODE was adopted with a fixed injection pressure of 80 MPa. Gasoline was injected through a port fuel injector installed in the intake manifold, with a self-developed gasoline injection control system allowing flexible adjustment of injection duration and timing. In this study, gasoline injection commenced at intake valve closing with a fixed injection pressure of 0.38 MPa, ensuring the formation of a well-mixed homogeneous charge. Cylinder pressure was measured using a Kistler-125C pressure sensor installed in the third cylinder, with real-time data acquisition and combustion analysis performed through a self-developed cylinder pressure processing system. Gaseous emissions were measured using a HORIBA MEXA-7100DEGR multi-component gas analyzer, while smoke emissions were measured with an AVL 415s filter paper smoke meter.

1.2 Experimental Method

In this study, the cycle fuel injection quantity (mg/cyc) for dual-fuel tests is defined as the equivalent gasoline quantity calculated based on the total energy content of the fuel entering the cylinder using the heating value of gasoline. IMEP (Indicated Mean Effective Pressure) is calculated based on the compression and expansion strokes, and the gasoline proportion Rp is defined as the ratio of gasoline energy content to the total energy content of fuel entering the cylinder.

The test speed was selected as 1500 r/min, with intake temperature controlled at $(38\$\pm1)^\circ C, enginecoolanttemperatureat(85\pm1)^\circ C, PODEtemperatureat(30\pm0.5)^\circ C, andgasolinetemperatur$
°C. To ensure accuracy and reliability of the test results, gaseous emissions were collected as 30-second averages after 2 minutes of stable engine operation, while smoke emissions were averaged from four consecutive measurements. All data presented in this paper were obtained under the following constraints: coefficient of variation (COV) $<$ 5%, maximum cylinder pressure Pmax $\leq$ 16 MPa, and maximum pressure rise rate MPRR $\leq$ 1.2 MPa/°CA.

2.1 Comparison of Diesel/Gasoline and PODE/Gasoline RCCI Combustion Modes

Figure 2 [Figure 2: see original paper] compares the combustion characteristics when diesel and PODE are used as direct injection fuels, respectively. The test conditions were: cycle fuel injection quantity of 50 mg/cyc equivalent gasoline, gasoline port injection proportion Rp of 80%, intake pressure of 0.2 MPa, and CA50 controlled at 7 °CA ATDC. It can be observed that under late-injection RCCI combustion mode, both diesel/gasoline and PODE/gasoline RCCI exhibit distinct two-stage heat release curves. The difference is that PODE does not show a low-temperature heat release stage but instead displays a depression in the heat release rate curve, which is attributed to the greater latent heat of vaporization due to higher injection quantities. Because PODE has a higher cetane number, its corresponding main injection timing is also relatively retarded while the injection duration is extended, resulting in a shorter ignition delay. However, the first-stage premixed heat release peak is significantly higher than that of diesel, primarily because PODE' s better volatility leads to faster mixing rates, and its higher ignition energy can ignite more premixed gasoline mixture. Due to the higher premixed heat release peak, the peak cylinder pressure is also slightly higher than that of diesel.

Figure 3 [Figure 3: see original paper] compares the emission characteristics when diesel and PODE serve as direct injection fuels. It can be seen that both diesel and PODE can achieve extremely low soot and NOx emissions across various EGR rates. Although PODE has a shorter ignition delay and larger injection volume, its high oxygen content of 48% can effectively suppress soot precursor formation, enabling PODE to achieve near-zero soot emissions. Due to its higher injection quantity, the effect of latent heat of vaporization is more pronounced, helping to reduce peak in-cylinder temperature. Additionally, influenced by its mixing rate, PODE' s NOx emissions are slightly lower than those of diesel. HC and CO emissions are relatively high in RCCI combustion mode, but PODE' s high oxygen content and higher ignition energy can effectively improve incomplete combustion product emissions, with more significant improvements observed under high EGR rates of 55%, consequently leading to slight improvements in thermal efficiency.

2.2 Effect of λ on Gasoline/PODE RCCI Combustion and Emissions

Figure 4 [Figure 4: see original paper] shows the combustion characteristics of PODE/gasoline RCCI under different excess air ratios λ. The test conditions were: cycle fuel quantity of 80 mg/cyc, intake pressure of 0.22 MPa, gasoline proportion Rp of 80%, and CA50 controlled at approximately 8 °CA ATDC through main injection timing. As the EGR rate increases and λ decreases, it can be observed that the corresponding main injection timing advances, but the ignition start point does not advance significantly, resulting in an extended ignition delay. The first-stage heat release rate peak increases with the advanced main injection timing, effectively suppressing the second-stage main heat release peak. The combustion duration is also significantly extended, leading to milder combustion. Particularly at $\lambda = 0.97$, due to the excessively early injection timing, the heat release rate exhibits a high-premixing single-peak heat release, and low-temperature reaction heat release reappears. This demonstrates that from the perspective of high-load extension, it is necessary to reduce λ as much as possible to control the combustion rate.

Table 3 presents the main combustion and emission parameters of PODE/gasoline RCCI at different λ values. It can be seen that as λ decreases, soot emissions remain controlled at extremely low levels, and even under fuel-rich conditions with $\lambda < 1$, no soot deterioration is observed.

Therefore, PODE can be considered to have characteristics that resist soot formation. Due to increased EGR rates, NOx emissions decrease significantly as λ is reduced. However, as λ decreases, HC and CO emissions increase, particularly CO emissions which surge in the near-stoichiometric region, leading to deteriorated combustion efficiency. Nevertheless, achieving stoichiometric combustion allows the use of simpler aftertreatment devices such as three-way catalysts to control HC/CO emissions. Although thermal efficiency also decreases due to combustion deterioration, it can still be maintained at a relatively high level above 44.5%. Comparatively, λ has a more pronounced effect on suppressing the maximum pressure rise rate, making it an effective means for high-load extension.

2.3 Combustion and Emission Characteristics with Different LIVC Timings

The late intake valve closing (LIVC) strategy can reduce the effective compression ratio and suppress excessively fast combustion heat release rates, representing an effective technical approach for extending high-load operation in diesel low-temperature combustion. This study employed a self-developed electro-hydraulic variable valve system to control the intake valve closing angle. Figure 5 [Figure 5: see original paper] shows the intake valve lift curves for different LIVC timings. Figure 6 [Figure 6: see original paper] illustrates the effect of LIVC timing on combustion. The test conditions were: cycle fuel quantity of 100 mg/cyc equivalent gasoline, intake pressure Pin = 0.22 MPa, Rp = 60%, λ 1.0, and CA50 controlled at 11 °CA ATDC. It can be observed that as the intake valve closing timing is retarded, the peak heat release rate decreases and the maximum cylinder pressure is effectively suppressed. Particularly at a LIVC angle of 50 °CA, both the maximum cylinder pressure and peak heat release rate are significantly lower than those of the original valve profile, thus effectively overcoming the constraints of cylinder pressure and pressure rise rate during high-load extension.

Figure 7 [Figure 7: see original paper] shows the effect of LIVC timing on emissions. Due to PODE’ s inherent resistance to soot formation, LIVC timing has minimal impact on smoke emissions, with near-zero smoke achieved across different LIVC angles. However, as the intake valve closing angle is retarded, despite the significant reduction in peak heat release rate, NOx emissions increase rapidly. This is primarily because retarding the intake valve closing timing causes a significant reduction in intake air quantity. To maintain stoichiometric combustion at $\lambda = 1$, the corresponding EGR introduction quantity is also reduced, leading to a substantial decrease in both the total in-cylinder working fluid mass and specific heat capacity. Consequently, the average in-cylinder temperature increases, resulting in elevated NOx emissions. HC and CO emissions show similar trends, first increasing and then decreasing. With retarded intake valve timing, the reduced compression density extends PODE spray penetration, increasing wall-impinged fuel quantity and fuel distribution in low-temperature regions at the combustion chamber periphery. Simultaneously, the relatively mild and slower combustion leads to increased HC and CO emissions. However, as the LIVC timing is further retarded, the increased average in-cylinder temperature enhances post-oxidation, with temperature becoming the dominant factor, thus improving HC/CO emissions.

2.4 High-load Extension of Gasoline/PODE RCCI

The adoption of LIVC can effectively suppress combustion rate and peak pressure, thereby allowing higher intake pressures for high-load extension. Table 4 shows the maximum load limits at various intake pressures with a LIVC angle of 55 °CA. Due to PODE' s inherent resistance to soot formation, peak cylinder pressure and pressure rise rate become the key controlling factors during high-load extension. In the tests, the maximum cylinder pressure was controlled at $P < 16$ MPa and the maximum pressure rise rate at $\text{MPRR} \leq 1.2$ MPa/°CA. To enhance stratification and strengthen combustion control through injection duration, the PODE injection quantity was increased, with Rp maintained in the relatively low range of 53%-56%.

Figure 8 [Figure 8: see original paper] shows the cylinder pressure and heat release rate achieved at maximum load under various intake pressures. The increased direct injection proportion can effectively control the second-stage heat release peak, overcoming the pressure rise rate limitation and enabling stoichiometric combustion, which facilitates the use of three-way catalysts for treating incomplete combustion products. Intake air quantity is the main factor limiting fuel quantity increase. As intake pressure increases, the in-cylinder burst pressure rises significantly, restricting further load increase. Therefore, further retarding of the LIVC angle is required to achieve even higher loads.

Figure 9 [Figure 9: see original paper] shows the emission characteristics at various loads during high-load extension. It can be seen that despite the high direct injection proportion and the phenomenon of fuel spray penetrating into the flame due to excessively long injection duration, extremely low smoke emissions can still be achieved. Due to high intake density and large EGR introduction quantity, the average in-cylinder temperature is effectively controlled, resulting in low NOx emissions. However, because λ is in the near-stoichiometric region, incomplete combustion products are relatively high, particularly CO emissions, which are highly sensitive to small fluctuations in λ. Consequently, indicated thermal efficiency is somewhat affected but can be maintained within a reasonable range above 40%.

3 Conclusions

This study investigated the combustion and emission characteristics of PODE/gasoline RCCI under different boundary conditions at 1500 r/min using PODE as the direct injection fuel, and conducted experimental research on high-load extension through high boosting combined with LIVC strategy. The main conclusions are as follows:

1) Compared with diesel/gasoline RCCI, PODE/gasoline RCCI combustion can achieve lower smoke emissions and significantly improve combustion efficiency and thermal efficiency.
2) Mixture concentration can effectively control the combustion heat release rate. In the stoichiometric region at λ 1, the combustion duration is extended and the maximum pressure rise rate is substantially reduced, while ultra-low smoke and NOx emissions can be achieved. The effective thermal efficiency can reach 44.5%–45.2%, but HC and CO are more sensitive to λ and their emissions deteriorate.
3) The adoption of the LIVC strategy can reduce cylinder burst pressure and peak combustion rate, but NOx increases due to reduced intake charge. Meanwhile, insufficient intake air becomes the main factor limiting high-load extension. PODE/gasoline RCCI stoichiometric combustion can achieve ultra-low soot/NOx emissions and effectively extend the high-load range. At a LIVC angle of 55 °CA, the maximum load is extended to 2.31 MPa IMEP while maintaining relatively high indicated thermal efficiency.

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Note: Figure translations are in progress. See original paper for figures.