Experimental study on in-cylinder combustion and exhaust emissions characteristics of natural gas/diesel dual-fuel engine with single injection and split injection strategies

Junheng Liu [a,*], Xuchao Zhang [a], Yuan Liu [a], Ping Sun [a], Qian Ji [a], Xidong Wang [a], Zhipeng Li [a], Hongjie Ma[b]

[a] School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China

[b] Institute of Industrial Research, University of Portsmouth, Portsmouth, Hampshire PO1 2EG, United Kingdom

*Corresponding author: Junheng Liu

Tel: +86-511-8879 7620

Fax: +86-511-8879 7620

Email address: liujunheng@ujs.edu.cn

Abstract: On a non-road, high-pressure common-rail engine, natural gas/diesel dual-fuel (NDDF) combustion mode was performed. The way natural gas energy substitution percentage (ESP) and pilot diesel injection timing affected the combustion process, emission properties and fuel economy regarding NDDF engine with single injection strategy and split injection strategy was experimentally investigated at 25% load of 1800rpm. Results show that under the two injection strategies, as ESP increased, NDDF combustion altered from single-stage to two-stage slowly, the combustion center (CA50) was delayed, the combustion duration increased, the soot and NO emissions declined, and the brake thermal efficiency (BTE) presented an increase-to-decrease change trend. As the combustion phase of split injection strategy was wholly advanced, the ignition delay period was shortened, the cyclic coefficient of variation (COV) and HC emission declined, and the BTE elevated. Additionally, the advanced injection timing would make NDDF heat release gradually advance, resulting in advanced CA50, extended ignition delay, lengthened combustion duration, lowered unregulated emissions, and increased BTE. The increase in peak heat release rate and BTE of split injection strategy was accompanied by decreased HC and aldehyde emissions. For NDDF engine possessing optimized split injection strategy, the BTE reached 37.79% and the COV reached 1.49% at ESP=60%.

Keywords: natural gas; low carbon combustion; pollutant control; split injection strategy; combustion efficiency; aldehyde emission

Nomenclature

ATDC	After top dead center
BSEC	Brake specific energy consumption
BTE	Brake thermal efficiency
CA	Crank angle
CA05	Combustion start point
CA50	Combustion center
CA90	Combustion endpoint
COV	Cyclic coefficient of variation
CR	Compression ratio
DF	Dual-fuel
EGR	Exhaust gas recalculation
ESP	Energy substitution percentage
HCCI	Homogeneous charge compression ignition
HRR	Heat release rate
HRRP1	The peak value of first heat release rate
HRRP2	The peak value of second heat release rate
ICEs	Internal combustion engines
ITE	Indicated thermal efficiency
LTC	low-temperature combustion
MPRR	Maximum pressure rise rate
NDDF	Natural gas/diesel dual-fuel
PCCI	Premixed charge compression ignition

P_{max}	Maximum in-cylinder pressure
Q_{pilot}	Pilot injection quantity
RCCI	Reactivity controlled compression ignition
SOI_{main}	Main injection timing
SOI_{pilot}	Pilot injection timing
SR	Swirl ratio
TDC	Top dead center

1. Introduction

As the main power of road traffic, non-road mobile machinery and national defense equipment at present, the application and development of internal combustion engines (ICEs) has greatly improved the efficiency of agricultural production, as well as made great contributions to the industrialization development and socio-economic progress of all countries in the world (Li et al., 2021). Diesel engine, with extraordinary thermal efficiency (Gholami et al., 2022) and output torque (Wei et al., 2022)2021, as well as excellent durability, has been extensively used in a variety of industries, including large heavy vehicles, ships and construction equipment (Wen et al., 2023; Chen et al., 2019). However, diesel engine is confronted with achieving lower emissions and higher thermal efficiency while shouldering the mission of alleviating the fossil energy crisis and dealing with strict emission regulations (Ren et al., 2021), and governments around the world have promulgated increasingly stringent emission regulations due to the growing concern about global climate change (Foroutan et al., 2021; Li et al., 2018a). Therefore, in the context of carbon neutralization and electrification, researchers have developed and executed various methods to seek the sustainable pathway for ICEs. The higher cost and complex control strategies hampered the application and development of post-processing system technology. The search for low-carbon clean alternative fuels and the application of lean compression ignition low-temperature combustion (LTC) strategies, like homogeneous charge compression ignition (HCCI) (Wu et al., 2021; Musculus et al., 2013; Niklawy et al., 2022), premixed charge compression ignition (PCCI) (Salahi and Gharehghani, 2019) and reactivity controlled compression ignition (RCCI) (Koç and Şener, 2021), as well as other innovative efficient combustion methods to improve the fuel utilization and optimize the reaction pathway, are important ways to achieve clean combustion and lead the ICEs technology to realize leapfrog innovation and development in the future.

LTC adopts partial or complete mixing of fuel and air before combustion, for avoiding a large equivalence ratio in the cylinder, along with a large exhaust gas recirculation (EGR) (Asad and Zheng, 2014) for evading the generation area of NOx, as well as a larger compression ratio (CR) for ensuring higher brake thermal efficiency (BTE) for the engine. HCCI combustion mode can achieve multi-point simultaneous compression ignition and rapid combustion heat release, which can significantly improve fuel economy. However, HCCI technology is extremely sensitive to boundary conditions and lacks effective control over variable operating conditions, resulting in its narrower effective operating zone (Agarwal et al., 2017). Compared with HCCI combustion mode, PCCI technology can realize the mixture concentration stratification in the cylinder, so as to regulate the combustion rate and ignition timing (Pandey et al., 2018). Moreover, the EGR and CR can be combined with fuel injection strategy to obtain higher BTE and lower emissions (Jain et al., 2017). However, PCCI combustion mode still encounters challenges of unstable combustion at low load. Considering the limitations of the above combustion modes, then the RCCI mode was put forward (Reitz and Duraisamy, 2015). The homogeneous combustible mixture formed by premixed inlet is ignited by the highly reactively fuel directly injected into the cylinder, which achieves in-cylinder reactivity stratification and broadens the operation range of efficient and clean combustion of dual-fuel (DF) engine by adjusting the premixed proportion and injection strategy (Zhou et al., 2021)2017. Bio-fuels (Li et al., 2018b), ammonia (Li et al., 2022) and natural gas are considered as alternative fuels with bright prospects in the field of ICEs, among which natural gas, as the third largest energy source in the world, is mainly composed of methane (Chen et al., 2021), which has higher calorific value, excellent antiknock performance (Navarro et al., 2013) and lower hydrocarbon ratio (Sharma et al., 2021) compared to diesel. It can achieve lean combustion under high CR along with 20~30% CO_2 emission reduction (Yousefi et al., 2018). With its low-carbon and clean characteristics, natural gas has been widely applied in vehicles, ships and other fields, and is considered as the most promising alternative fuel for ICEs in the 21st century (Singh et al., 2019). On the basis of the baseline engine structure, an additional natural gas supply and control system is equipped in the intake port to realize RCCI combustion by igniting premixed natural gas with direct injection diesel in the cylinder at a low cost (Bayramoğlu and Özmen, 2021) and flexible switching mode (Johnson et al., 2017), so as to broaden the operating range of the engine while achieving lower soot emission (Poorghasemi et al., 2017).

Nevertheless, there are still certain difficulties with the actual utilization of natural gas/diesel dual-fuel (NDDF) RCCI mode. Firstly, the ignition energy of premixed natural gas is high at low load, and the mixtures in the narrow gap areas and near wall areas may not be able to burn completely, which will lead to high CO and HC emissions. Additionally, the slow flame speed propagation of natural gas gives rise to reduced combustion efficiency and deteriorated combustion stability, resulting in lower BTE (Park et al., 2019; Duan et al., 2021). Secondly, under the RCCI diesel micro-ignition mode, the small amount of pilot fuel at low load will inevitably lead to poor combustion stability and even misfire. In view of the above problems, relevant scholars and researchers have experimentally found that adjusting the parameters such as natural gas or diesel injection timing and EGR rate can optimize RCCI combustion of NDDF engine. Yousefi and Birouk (2017) investigated how the energy substitution percentage (ESP) and pilot diesel injection timing impacted the fuel economy and emission characteristics exhibited by NDDF engine. They concluded that indicated thermal efficiency (ITE) reached a maximum value of 26.7% at 50% ESP when the diesel injection timings were -12°crank angle (CA) after top dead center (ATDC) and -20°CA ATDC. Moreover, compared with pure diesel mode, the NOx emissions decreased substantially at 60% ESP. Hernández et al. (2016) explored the impacts of H_2, CH_4 and CO additions on combustion efficiency and pollutant emissions. According to their findings, the introduction of hot EGR gas increased engine combustion efficiency. Additionally, the trade-off between NOx and soot also decreased possibly because of the inclusion of gaseous fuels and a high EGR rate.

The researchers also investigated the in-cylinder combustion process of NDDF mode through numerical simulation and optical testing. Huang et al. (2019) conducted experimental and numerical simulation research on NDDF engine combustion process and emission properties under low load. It was observed that the combustion start point (CA05) was mainly controlled by the main injection timing (SOI_{main}) when the pilot injection timing (SOI_{pilot}) was earlier. Specifically, when the SOI_{pilot} was -50°CA ATDC, the ITE of 41.2% and lower CH_4, CO and NOx emissions were achieved. Yousefi et al. (2018) examined how swirl ratio (SR) affected NDDF engine performance and emission characteristics under different load conditions through numerical simulation. The findings demonstrated that an increase in SR could dramatically improve fuel economy as well as CH_4 emissions at small load. Lee et al. (2020) conducted an experimental study to determine how ESP affected the flame development and soot emission characteristics of NDDF optical engine. As found, the flame core was formed in multiple regions near the cylinder wall and then propagated toward the center. With the increase of ESP, the area of premixed flame peak became larger, the high-temperature region and soot volume fraction decreased. Higher ESP would lead to cleaner combustion trend and more desirable flame characteristics.

The investigation of chemical reaction kinetics mechanism is an important way to deeply understand the influences of mixture stratification and reactivity stratification on efficient and clean combustion process of NDDF diesel. Gong et al. (2020) explored the ignition reaction mechanism of n-heptane/methane mixtures by using the zero-dimensional constant volume adiabatic reactor simulation in Chemkin-Pro and shock tube tests. The research showed that increasing the content of n-heptane significantly shortened the DF ignition delay period, while the addition of methane would slightly suppress the spontaneous ignition of n-heptane, and n-heptane also presented noticeably quicker reaction time relative to methane. Liang et al. (2019) found that there was a nonlinear relationship between the ignition delay period of n-heptane/methane mixtures and methane content through the study of shock tube tests and NUI mechanism. The period until methane had been completely consumed was accelerated by the rise in n-heptane concentration. Additionally, n-heptane possessed the improved capability to interact with free radicals. Liu et al. (2019) coupled the n-heptane ignition mechanism (44 steps reaction) with natural gas skeletal mechanism (18 steps reaction) to form a NDDF combustion reaction mechanism. Consequently, declined methane level led to prolonged ignition delay period of the mixture. The combustion reaction virtually stopped when the methane equivalent ratio reached 0.3 because the low-temperature intermediate product CH_2O was exhausted, and the engine misfired as a result. Moreover, the increase of methane equivalent ratio could increase the power of the engine, but it would cause pressure oscillation and promote the generation of NOx.

At present, the engine performance of NDDF RCCI combustion under high load and the influencing factors of in-cylinder combustion process have been fully investigated. However, existing research on NDDF RCCI combustion mode generally revealed the problems of unstable combustion, even misfires and extremely deteriorating emissions at low load. Many scholars have carried out detailed research on performance parameters and cycle variations of NDDF engine under various boundary conditions. Nevertheless, spark ignition natural gas engines have been extensively studied, and few studies have been conducted on diesel-ignited NDDF engine with in-cylinder direct injection. Additionally, the BTE of an NDDF engine operating in the conventional combustion mode might be significantly improved by slightly earlier diesel injection timing, but it was accompanied by the increase of NOx emissions (Li et al., 2017).

While the earlier ignited diesel injection strategy could reduce pollutant emissions and improve BTE, it encountered the problem of poor combustion stability due to inconsistent combustion start point. Furthermore, the majority of existing studies only focused on the isolated research of control parameters like single injection strategy, EGR rate, and intake temperature, whereas the comprehensive research of high natural gas ESP combined with combustion control strategy under low load conditions is not perfect.

The study aims at improving the natural gas ESP and combines with a pilot diesel injection strategy to achieve efficient and clean agricultural power work, so as to provide theoretical and experimental guidance for optimizing the diesel injection strategy and improving the performance for NDDF mode. Consequently, a four-cylinder, electronically controlled common-rail non-road diesel engine that has been modified to implement the NDDF combustion mode is the basis for this investigation. Systematic research has been carried out from the perspective of improving combustion and controlling pollutants with various ESP and injection strategies under small load. To determine the ideal value of ESP, it is first compared the impacts of ESP on combustion and emission properties employing single injection and split injection strategies. Additionally, for a fixed ESP of 60%, the impacts of SOI_{main} on improving combustion properties and lowering pollutant emissions of NDDF engine are explored.

2. Experimental apparatus and test methodology

2.1. Experimental apparatus

Table 1 gives the technical specifications regarding experimental baseline engine. The injection system of the original engine was retained for the supply and control of direct injection diesel, and an additional set of natural gas supply and injection control systems was added, so as to realize the NDDF combustion mode. Fig. 1 gives a schematic diagram regarding the experimental system, which mainly includes the fuel supply system, the control system, the test system, the data acquisition system, the emission acquisition and the analysis system of NDDF engine. The 20MPa natural gas in the compressed gas cylinder was depressurized to 0.5MPa through the pressure-reducing valve, and heated by the heat exchanger during the depressurization process to prevent the pressure from falling suddenly and freezing. Then, it flowed to the natural gas flowmeter and the gas rail through the pressurizer and filter. Finally, it was introduced into the intake port for generating a homogeneous premixed gas. 0.5MPa was selected as the natural gas injection pressure, and the self-made port injection controller helped to regulate the injection duration of natural gas in real-time considering the engine operating conditions. In this experiment, the pilot injection quantity (Q_{pilot}), SOI_{pilot} and injection pressure of ignited diesel were controlled by INCA calibration software.

During the test, the measurement and control system of the NDDF engine is the FC2000 automatic engine measurement and control system. The pressure transducer (GH14P, AVL, Austria) was employed to gather the cylinder pressure signal while the combustion analyzer (INDIMODUL 622, AVL, Austria) determined the in-cylinder pressure. Natural gas injection valve (NGI2 0280158821, BOSCH, Germany) was employed to regulate the injection quantity of natural gas. An exhaust gas analyzer (MEXA 7200D, Horiba, Japan) measured the regulated emissions. By using a multi-component gas analyzer (SESAM-FTIR, AVL, Austria), the unregulated emissions (NO_2, N_2O, HCHO, CH_3CHO, C_2H_4 and C_3H_6) were assessed.

Table 1 Test engine technical specifications.

Engine parameters	Specification
Engine type	In-line 4-cylinder, turbocharged intercooler
Displacement (L)	3.26
Bore × stroke (mm × mm)	105 × 125
Rated power/speed (kW/rpm)	88/2200
Maximum torque/speed (Nm/rpm)	270/1800
Maximum injection pressure (MPa)	160
Combustion chamber	ω
Compression ratio	17.5:1
Injection system	Electronically controlled common-rail system
Intake valve closure (°CA ATDC)	-130
Exhaust valve opening (°CA ATDC)	120

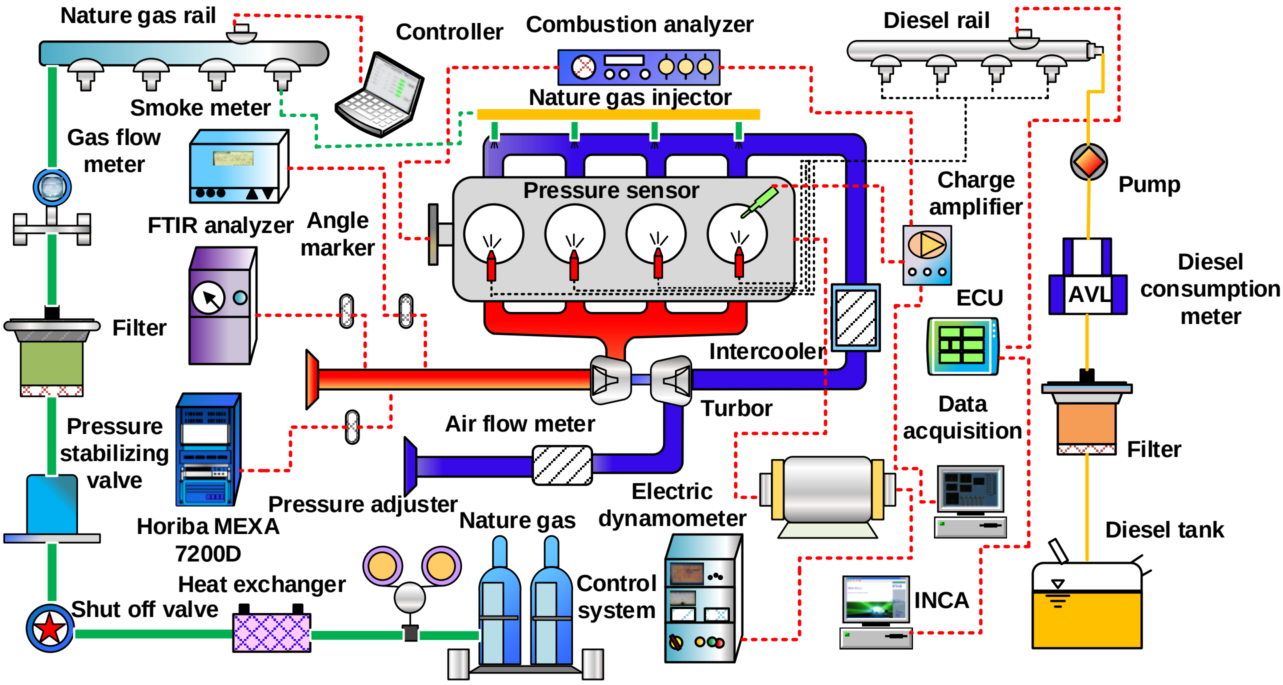


Fig. 1. Schematic diagram of the engine test rig.

2.2. Test fuels

In NDDF combustion mode, natural gas with 99% methane content was used for intake injection and commercially available Euro VI diesel was used for in-cylinder direct injection. The primary physicochemical characteristics of natural gas and diesel in the tests were shown in Table 2. The nature gas ESP in NDDF mode is defined as follows:

$$ESP = \frac{m_{NG} \times LHV_{NG}}{m_{NG} \times LHV_{NG} + m_{diesel} \times LHV_{diesel}} \times 100\% \quad (1)$$

where, m_{diesel} and m_{NG} represent the cycle injection quantity of natural gas and ignited diesel under NDDF mode, respectively, kg/cycle; LHV_{NG} and LHV_{diesel} respectively denote their low calorific values, MJ/kg.

Table 2 Properties of diesel, gasoline and natural gas.

Fuel type	Diesel	Gasoline	Methane
Chemical formula	C_{10}~C_{21} hydrocarbon	C_5~C_{12} hydrocarbon	CH_4
H/C ratio	1.9	0.45	3.96
Density (g/cm^3) @ 20 °C	0.83	0.000732	0.00796
Auto-ignition temperature(°C)	270~350	427	650
Octane number	-	86~94	130

Cetane number	44~45	-	3
Boiling point (°C)	180~360	30~220	-162
Lower heating value (MJ/kg)	42.5	44	50
Vaporization latent heat (KJ/kg)	270	289	-
Stoichiometric air-fuel ratio (kg/kg)	14.3	14.8	17.2
Viscosity (mm^2/s) @ 20 °C	3.564	0.64	0.011

2.3. Experimental procedure

In the experiment of this study, 25% load at the largest torque speed (1800rpm) was selected. Our team controlled the intake air temperature and coolant temperature in a closed loop at 35±2°C and 80±2°C, respectively. During the experiment, the characteristic parameters in the combustion process were calculated considering the in-cylinder pressure data of 100 consecutive engine cycles. Conforming to the first law of thermodynamics as well as the ideal gas law, we calculated the heat release rate (HRR) of the engine by the average pressure in the cylinder. The corresponding CA when the accumulated heat release reaches 5%, 50% and 90% of the total heat release are defined as the CA05, combustion center (CA50) and combustion endpoint (CA90), respectively. The cyclic coefficient of variation (COV) is considered to assess NDDF engine combustion stability, and Eq. (2) is used to calculate the COV.

$$COV = \frac{\sigma_{IMEP}}{IMEP} \times 100\% \tag{2}$$

Eq. (3) and Eq. (4) are used to determine BTE and brake specific energy consumption (BSEC), where, P_e represents the effective output power of NDDF engine.

$$BTE = 3.6 \times \frac{P_e}{m_{NG} \times LHV_{NG} + m_{diesel} \times LHV_{diesel}} \times 100\% \tag{3}$$

$$BSEC = \frac{m_{NG} \times LHV_{NG} + m_{diesel} \times LHV_{diese}}{P_e} \tag{4}$$

Before the test, the top dead center (TDC) position was calibrated by the combustion analyzer. During the test, the engine ran stably in pure diesel mode at 25% load to obtain the diesel injection quantity of the baseline engine. In the process of engine mode switching, the output torque was kept constant, then the diesel injection quantity was gradually reduced by INCA control software, and the natural gas injection quantity was increased synchronously until the predetermined ESP was attained. The engine now switched to the anticipated NDDF combustion mode and subsequent measurements could be carried out once the engine operated steadily.

The contents of current research consist of the following two parts. First, the influences of ESP on the engine performance of NDDF mode with diesel single injection strategy and split injection strategy were investigated separately. Based on the working condition of the original diesel engine, the SOI_{pilot} of -30°CA ATDC was chosen. The influences of ESP on improving combustion and controlling pollutants of NDDF engine with these two injection strategies were analyzed comparatively. Then, the influences of SOI_{main} on the engine performance of NDDF mode with two injection strategies were also investigated. The ideal value of ESP was selected as in NDDF mode was fixed at 60%, and the pilot injection parameters and injection pressure were also consistent with the baseline engine.

The engine ran continuously for 5 minutes under the appropriate operating settings in each group of testing circumstances to collect the precise measured parameters. Additionally, the entire experiment method was performed twice, and all test points were conducted five times for obtaining the average value. Table 3 displays the specification and uncertainty of the measurement instruments.

Table 3 Uncertainties of measured parameters.

Instrument	Measured parameter	Range	Accuracy	Uncertainty (%)
Electric dynamometer	Speed	0~5000 rpm	0.03%	-
	Torque	0~700 Nm	0.4%	-
Fuel consumption meter	Diesel consumption	0~50 kg/h	0.12%	0.6
	NG consumption	0~30 kg/h	0.08%	0.5
Pressure transducer	In-cylinder pressure	0~15 MPa	0.01MPa	0.2
Angle marker	Crank angle	-	0.1°CA	-
Smoke meter	Soot	0~10 FSN	0.001FSN	0.4
Exhaust gas analyzer	HC	0~5000 ppm	2ppm	1.2
	CO	0~50000 ppm	2ppm	1.2
	NOx	0~1000 ppm	1ppm	1.5

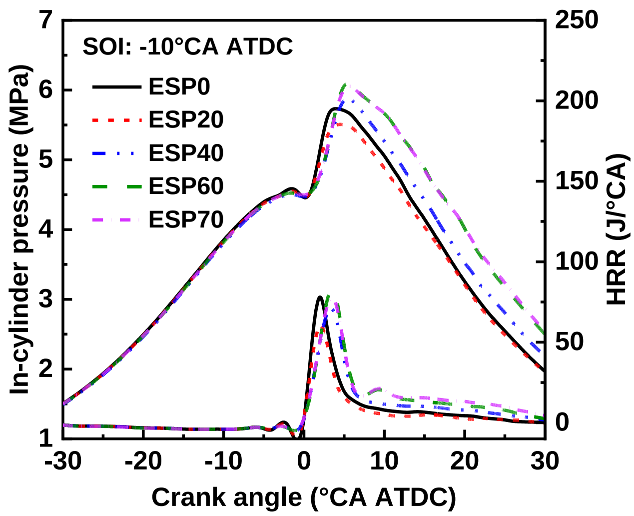
FTIR analyzer	NO, NO_2	0~1000 ppm	1ppm	2.5
	N_2O	0~50 ppm	1ppm	2.0
	HCHO, CH_3CHO	0~500 ppm	1ppm	2.1
	C_2H_4, C_3H_6	0~300 ppm	1ppm	2.1

3. Results and discussion

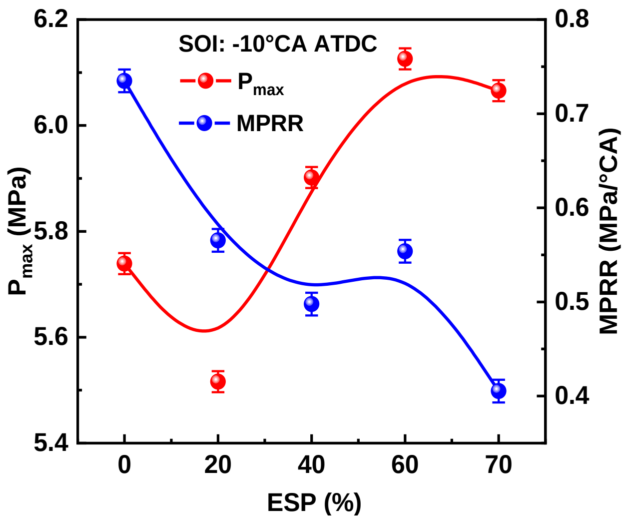
3.1 Influence of ESP on NDDF engine performance

3.1.1 Combustion characteristics

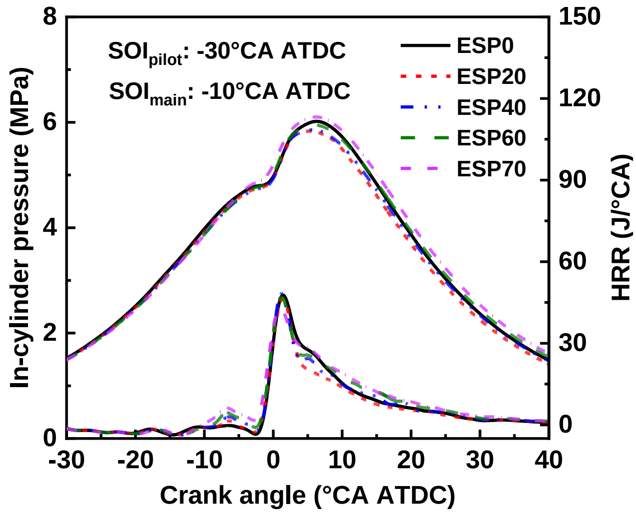
The influences of different ESP on in-cylinder pressure and HRR regarding NDDF engine with single injection and split injection strategies under 25% load are presented in Fig. 2. It is observed that under the two injection strategies, the compression curve and maximum in-cylinder pressure (P_{max}) of NDDF mode exhibit a tendency of dropping initially and subsequently increasing with the increase of ESP, while the maximum pressure rise rate (MPRR) presents a decrease-to-increase change trend. As illustrated in Fig. 2 (a) and Fig. 2 (b), under the single injection strategy, when ESP reaches 70%, the P_{max} decreases slightly. With the increase of ESP, the peak HRR first decreases and then increases. When ESP exceeds 40%, the HRR curve progressively changes from single-peak to double-peak, and the peak phase of HRR continues to retard. Additionally, the peak value of first HRR (HRRP1) initially rises and then falls, and the HRRP1 is always much larger than the peak value of second HRR (HRRP2). This is attributable to the fact that when ESP is less than 40%, it will lead to a prolonged ignition delay period, and the diesel has been completely atomized before the start of combustion. At this time, the single-stage premixed combustion of diesel is dominant in the cylinder. The ignition delay period of diesel increases significantly as ESP rises, and more diesel premixed gas is formed, which accelerates the premixed combustion rate, resulting in the increase of HRRP1 along with the elevated P_{max} and MPRR. When ESP is greater than 60%, more natural gas with high heat capacity and low reactivity will participate in in-cylinder combustion. At this time, the amount of ignited diesel is greatly reduced, the diesel premixed combustion rate gradually decreases, the HRRP1 dominated by ignited diesel gradually decreases, the HRRP2 formed by natural gas flame propagation combustion gradually increases, and then the whole combustion heat release process tends to be gentle. The overall in -cylinder reactivity of the fuel is very low at this time, and the stratification degree of in-cylinder fuels is also more obvious, which makes it difficult for the thin mixture around the diesel spray to support the turbulent flame propagation caused by a small amount diesel. The combustion rate of the mixture decreases, resulting in the decrease of P_{max} and MPRR. It is viewed from Fig. 2 (c) and Fig. 2 (d) that the P_{max} and MPRR both decrease first and then increase as ESP increases when the split injection strategy is adopted. Relative to the single injection strategy, the fluctuation range of P_{max} and MPRR under the split injection strategy is reduced. When ESP increases, the pilot injection diesel heat release is progressively advanced and enhanced. When ESP is greater than 40%, the HRR still presents a bimodal state. The premixing and low-temperature reaction of pilot injection diesel improve in-cylinder mixture reactivity distribution, meanwhile weakening the stratification tendency regarding in-cylinder mixture, which advances the heat release of the second stage, thus improving the combustion property exhibited by NDDF engine with high ESP.



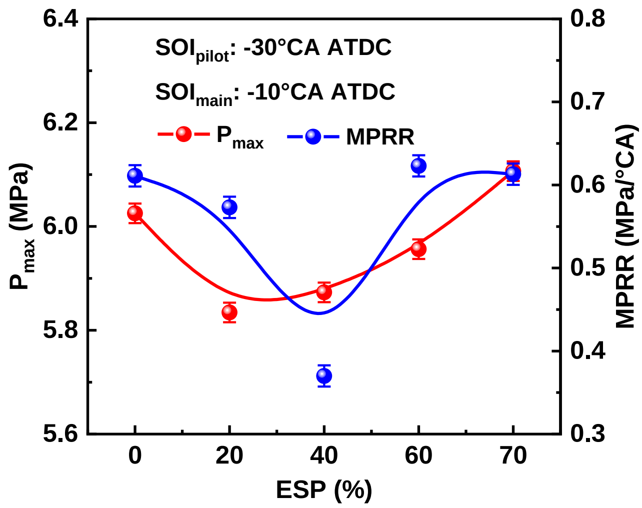
(a) In-cylinder combustion with single injection



(b) P_{max} and MPRR with single injection



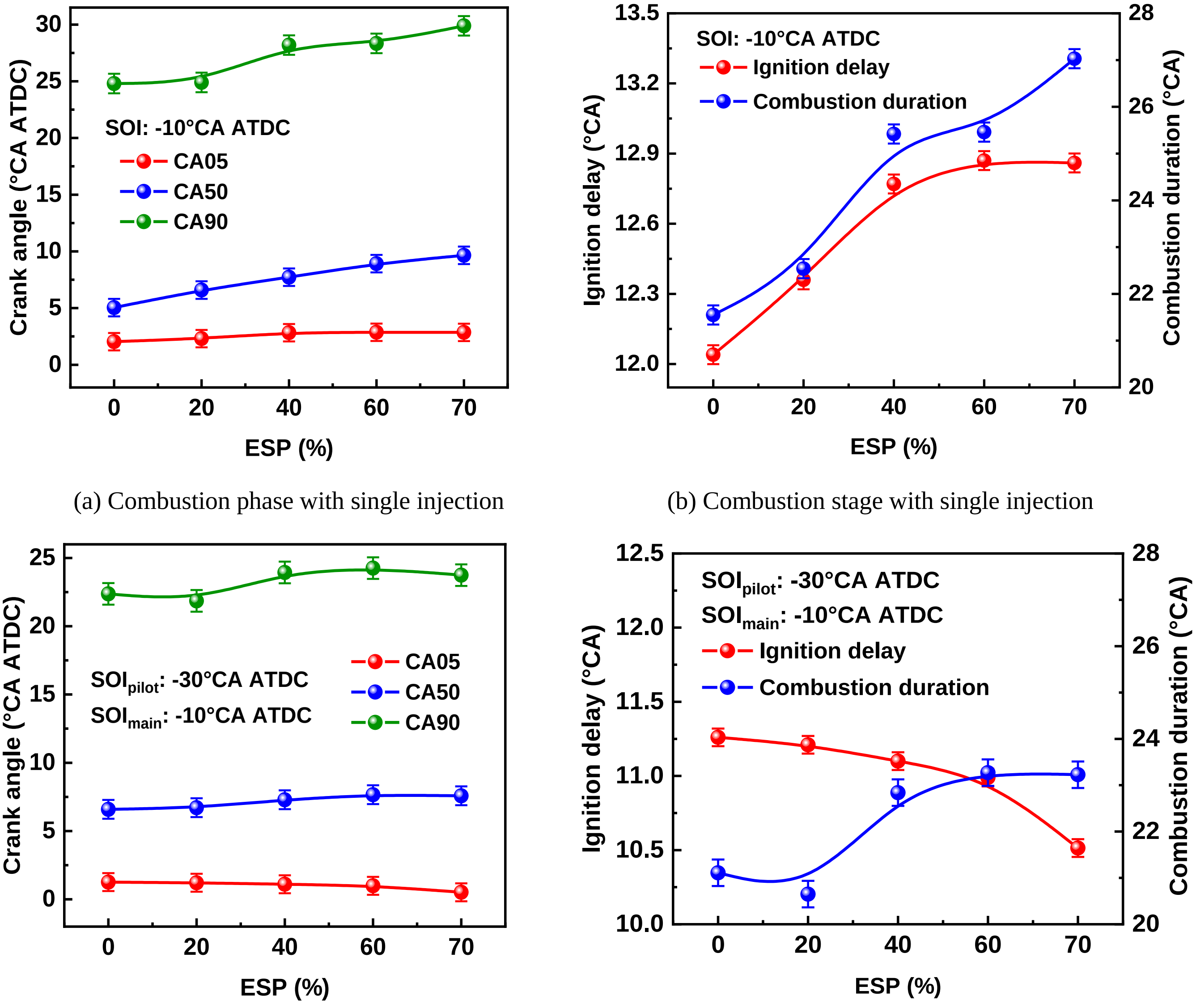
(c) In-cylinder combustion with split injection



(d) P_{max} and MPRR with split injection

Fig. 2. Influences of ESP on in-cylinder pressure and HRR of NDDF engine at 25% load.

Fig. 3 depicts the in-cylinder combustion process variation pattern of NDDF engine with different ESP under two injection strategies at 25% load. As illustrated in Fig. 3 (a) and Fig. 3 (b), the CA05 is slightly delayed as ESP increases, while the CA50 and CA90 are continuously delayed, and the ignition delay period and combustion duration gradually increase, because increased ESP reduces the pilot diesel amount and the natural gas ignition energy. More natural gas with high heat capacity takes up part of the fresh air volume in the intake process, so that the oxygen concentration in the cylinder decreases, resulting in increased overall specific heat capacity of in-cylinder working medium, decreased compression temperature and the slowdown of chemical reaction rate of diesel before ignition. This would cause an increased ignition delay period and combustion duration of diesel fuel. Additionally, when ESP increases, the diesel distribution range becomes smaller at the beginning of the chemical reaction, and the stratification tendency of in-cylinder mixture becomes more obvious. The overall reactivity of the fuel in the cylinder and the ignition energy decrease, the combustion rate of combustible mixture is reduced, and the range of multi-point ignition is also decreased, which ultimately leads to a longer combustion duration. According to Fig. 3 (c) and Fig. 3 (d), the CA05 of NDDF combustion mode is advanced, and the CA50 and CA90 are continuously postponed as the ESP increases. The CA50 and CA90 are more advanced, as well as being considerably shorter than with the single injection strategy in terms of the ignition delay period, because the increased ESP gradually advances and enhances the heat release process in the first stage. The premixing and low-temperature reaction presented by pilot injection diesel improves the reactivity of the mixture, accelerates the generation of combustion products and activation groups in the mixture, and forms a certain reactivity stratification of in-cylinder fuel (Splitter et al., 2011), which ultimately shortens the ignition delay period. At high ESP, the CA05 and CA90 under split injection strategy are significantly advanced, and the performance of NDDF engine is effectively improved.



(a) Combustion phase with single injection

(b) Combustion stage with single injection

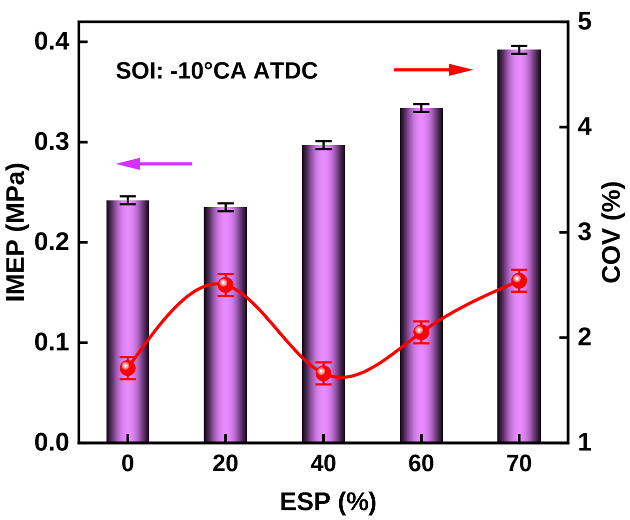
(c) Combustion phase with split injection

(d) Combustion stage with split injection

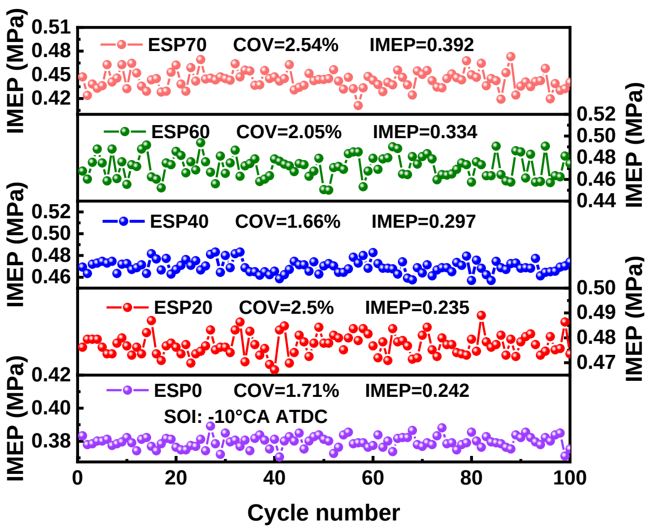
Fig. 3. Influences of ESP on NDDF engine in-cylinder combustion process at 25% load.

The effects of different ESP on IMEP and COV of NDDF engine with two injection strategies at 25%

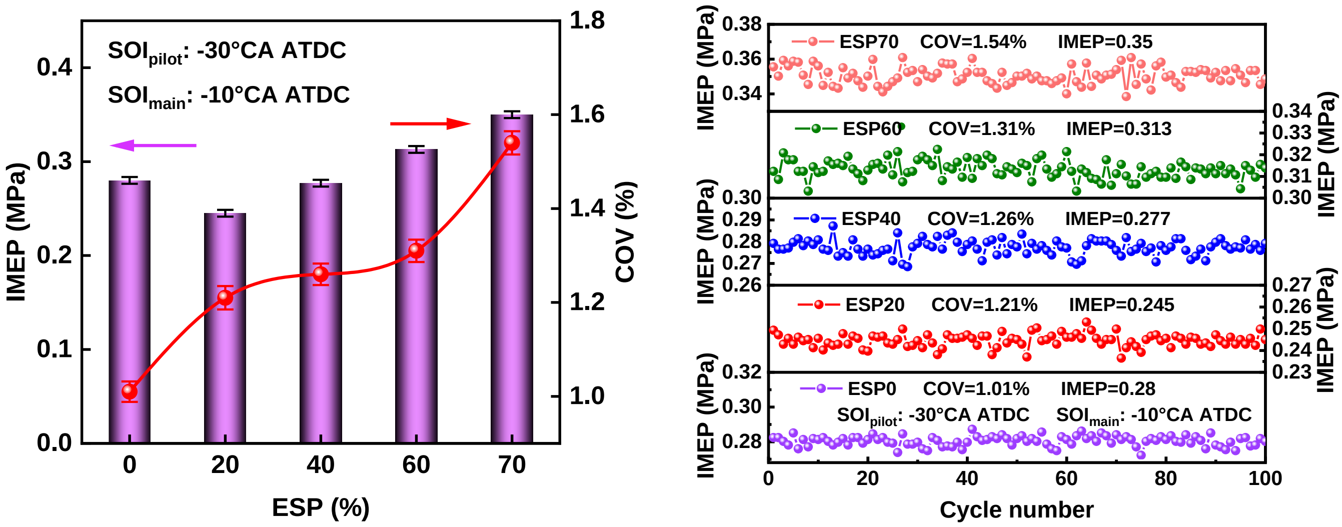
load are exhibited in Fig. 4. As shown in Fig. 4 (a) and Fig. 4 (c), the IMEP of NDDF engine under both injection strategies decreases slightly at first and then increases gradually as ESP increases, and fluctuates within a small range of 0.2~0.4MPa. However, the change of IMEP under split injection strategy is more stable. As illustrated in Fig. 4 (b) and Fig. 4 (d), elevated ESP leads to the rise of COV. This is because the increased ESP enhances the certain heat capacity in the cylinder, and decreases the overall reactivity of in-cylinder fuel, and the CA50 is gradually delayed, and then more fuel will participate in the combustion after TDC. Meanwhile, the lean natural gas mixture in the cylinder can hardly support the propagation of turbulent flame caused by trace diesel due to the low local equivalent ratio, which makes the rate of natural gas premixed combustion decrease and the premixed combustion more unstable, resulting in the increase of COV of NDDF engine (Wang et al., 2021). In addition, the COV fluctuation under the split injection strategy is relatively stable, and the overall COV is reduced, which is less than 2.0%.



(a) IMEP with single injection



(b) Cyclic variation with single injection



(c) IMEP with split injection

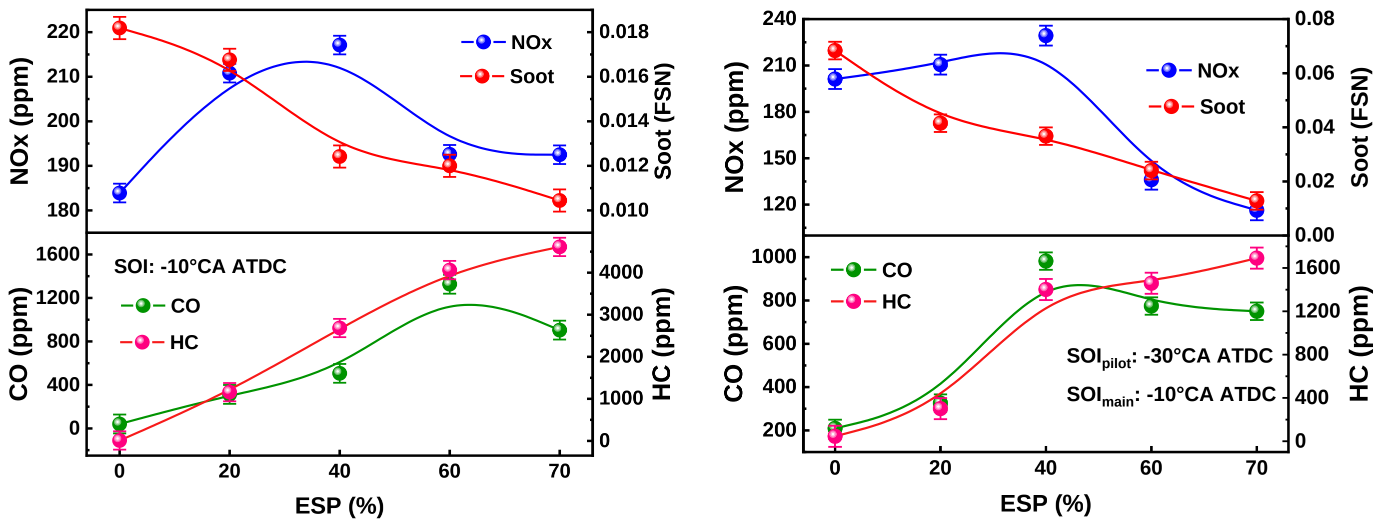
(d) Cyclic variation with split injection

Fig. 4. Influences of ESP on IMEP and COV of NDDF engine at 25% load.

3.1.2 Emission characteristics

The influences of different ESP on regulated emissions regarding NDDF engine with two injection strategies at 25% load are shown in Fig. 5. It is found that NOx and CO emissions of NDDF combustion mode exhibit a trend of rising first and then gradually decreasing as ESP increases, while HC emission shows an upward trend under the two injection strategies. This is because NOx generation can be impacted by the mixture concentration and reaction time in the cylinder (Ouchikh et al., 2022). As ESP elevates, the ignition delay period gradually is extended, the premixed diesel combustion rate is accelerated, and the combustion temperature and pressure in the cylinder rise, which increases NOx emissions. When ESP continues to increase, more natural gas with high heat capacity and low reactivity participates in the combustion process, which decreases the charging efficiency and oxygen concentration. The natural gas mixture hinders the propagation speed of turbulent flame, reduces the intensity of diesel premixed combustion and local high-temperature area, which lowers NOx emissions. Uneven mixing of fuel and air will lead to local hypoxia and CO generation (Zhu et al., 2022). As ESP increases, the overall reactivity of the fuel in the cylinder decreases, and the stratification degree of diesel and mixture increases under the single injection strategy. Due to the low local equivalence ratio of combustible mixture, the combustion is poor, and the CO oxidation reaction is blocked, resulting in increased CO emission. Additionally, the natural gas is injected into the intake port, so that the charging efficiency and oxygen concentration decrease at higher ESP, which affects the further oxidation of CO. When ESP continues to increase, it leads to a prolonged ignition delay period, and ignited diesel and air mix more uniformly, resulting in a decrease in CO emission. The probability of wall quenching effect of natural gas homogeneous mixture in the cylinder increases as ESP increases. The temperature around the cylinder wall and piston gap is low, which rapidly cools the combustion flame, interrupting flame propagation, and enhancing HC emission. Moreover, when ESP increases, the ignition energy resulted from ignited diesel decreases, and the lean natural gas mixture in the cylinder can hardly support the propagation of turbulent flame because of the low local equivalence ratio, lowering the combustion rate and intensifying the incomplete combustion in the cylinder, and a large amount of unburned natural gas is directly excluded from the cylinder, thus increasing HC emission. Under the split injection strategy, the ignition delay period is shortened and the combustion phase is significantly advanced, which promotes the reaction to develop near the wall. The premixing and low-temperature reaction of pilot injection diesel in the cylinder improve the mixture reactivity distribution, hence, it presents obviously lower HC emission relative to the single injection.

Local hypoxia and incomplete atomization of the fuel in the cylinder will lead to the formation of soot. According to Fig. 5 (a) and Fig. 5 (b), the soot emissions under both injection strategies show a downward trend as ESP increases. Compared with the baseline engine (ESP0), the soot emission of ESP70 under the split injection strategy is reduced by 29.63%, because as ESP is on a rise, the proportion of natural gas heat release elevates, the ignited diesel amount gradually decreases, the proportion of diffusion combustion decreases, causing the gradual decrease of soot emission and the overall lower level. Moreover, methane is the main component of natural gas, which possesses a low hydrocarbon ratio and a single-carbon structure, and belongs to homogeneous premixed combustion. The increase of ignition delay period makes the diesel/natural gas mixture more uniform and sufficient, the local high-temperature and fuel-rich areas were reduced, while the maximum combustion temperature under low load is also low, which assists in reducing the soot formation. The split injection strategy exhibits higher overall soot emission relative to the single injection (Fig. 5 (b)). This is because under low load, the pilot injection diesel injected at -30°CA ATDC, the combustion pressure and temperature in the cylinder are comparatively lower, and partial diesel collides with the wall, resulting in insufficient mixing. While the local over-rich zone in the cylinder is also increased, resulting in some additional soot emission.

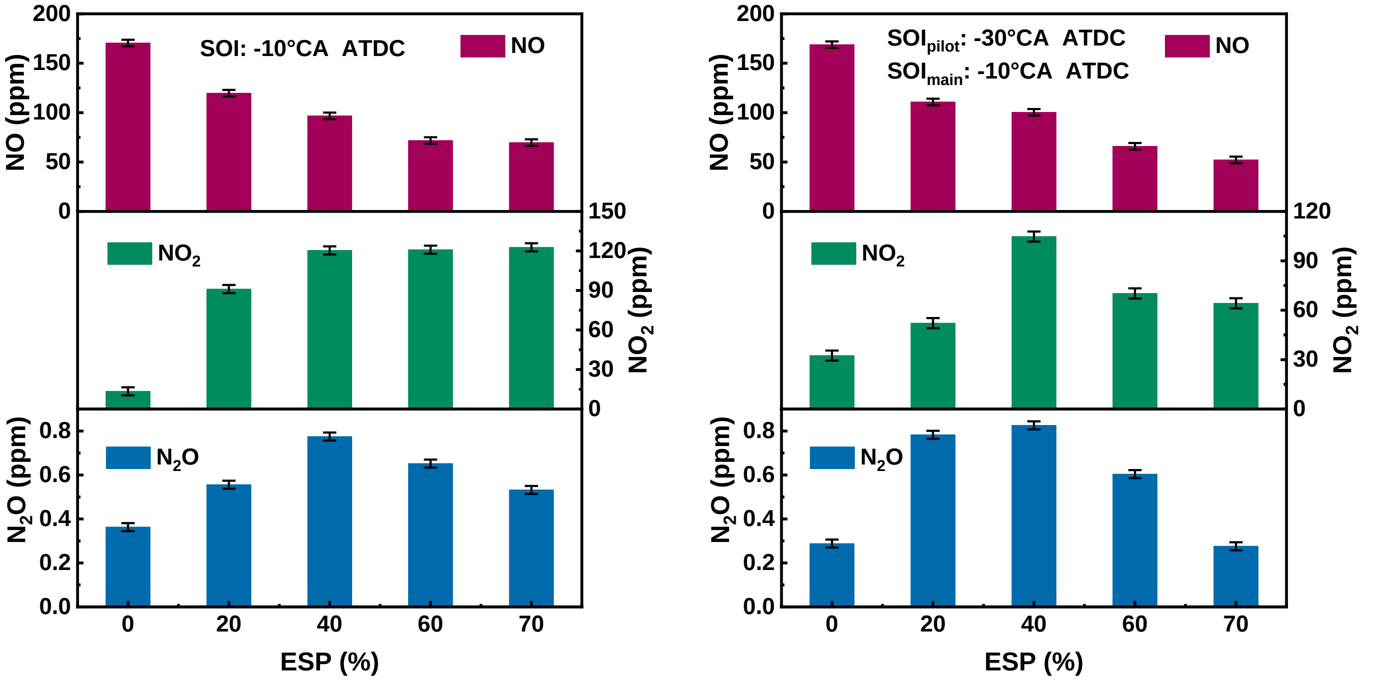


(a) Single injection (b) Split injection

Fig. 5. Effects of ESP on NDDF engine regulated emissions at 25% load.

Fig. 6 displays the influences of different ESP on NOx emissions of NDDF engine with single injection and split injection strategies at 25% load. NO, NO_2 and N_2O play a dominant role in NOx emissions, in which NO emission mainly comes from the high-temperature path, and the temperature and oxygen concentration in the cylinder are the main reasons for NO generation. As depicted in Fig. 6, under the single injection and split injection strategies, as ESP elevates, NO emission gradually decreases, and the downward trend of split injection strategy is more obvious, while NO_2 and N_2O emissions first increase and then gradually decrease. Under the split injection strategy, NO emission of ESP70 decreases by 69.31% relative to baseline engine, because part of the oxygen atoms generated by the flame propagation of natural gas ignited by diesel are distributed near the flame front surface, and some are distributed in the high-temperature area of diesel spray combustion, which are generated by H + O_2=O + OH reaction. With the increase of ESP, the oxygen concentration in the cylinder decreases. The generation of OH radicals that promote the reaction reactivity of the system is suppressed. Besides, the production rate of NO through the reaction of N_2 + O=N + NO is reduced. While, more natural gas forms premixed fresh charge with air in the intake port, that elevates the amount of premixed combustion in the cylinder, decreases the local high-temperature area, and destroys the generation conditions of NO. After the introduction of natural gas in the intake port, the overall high-temperature duration in the cylinder becomes shorter, which also limits NO generation. In addition, the residence time of the reactants in a high-temperature environment is short, and NO cannot reach the equilibrium concentration, resulting in the decrease of NO emission. While NO emission decreases and NO_2 emission increases. This is because adding natural gas transforms active OH radicals into relatively inactive HO_2. HO_2 promotes the formation of NO in the flame to fast convert into NO_2 because of NO + HO_2=NO_2 + OH reaction. Also, the generated NO_2 is frozen by mixing with cooler gas, resulting in an increase in NO_2 emission. At high ESP, the generation amount of NO is small, the generation rate of OH and HO_2 in the combustion chamber also slows down, and the overall reactivity of the fuel in the cylinder decreases, so that the degree of NO conversion to NO_2 through the reactions of O + NO (+M)=NO_2 (+M) and NO + HO_2=NO_2+ OH is weakened (Wei et al., 2015), which leads to the decrease of NO_2 emission. N_2O is mostly distributed in the flame, and the highest concentration is located in the area with low-temperature and low concentration of combustible mixture. The in-cylinder temperature decreases as the ESP increases, which is conducive to the conversion of NO into NO_2 through NCO + NO=N_2O + CO and 2NO + CO=N_2O + CO_2, thus leading to the increase of N_2O emission. At high ESP, the amount of NO generated is low, which reduces the rate of NO conversion to N_2O. Additionally, the appropriate combustion temperature and pressure in the cylinder make N_2O generated in the high-temperature area decompose into

NO and N_2 through $N_2O + O = 2NO$ and $N_2O (+M) = N_2 + O (+M)$ reactions, thus reducing N_2O emission.

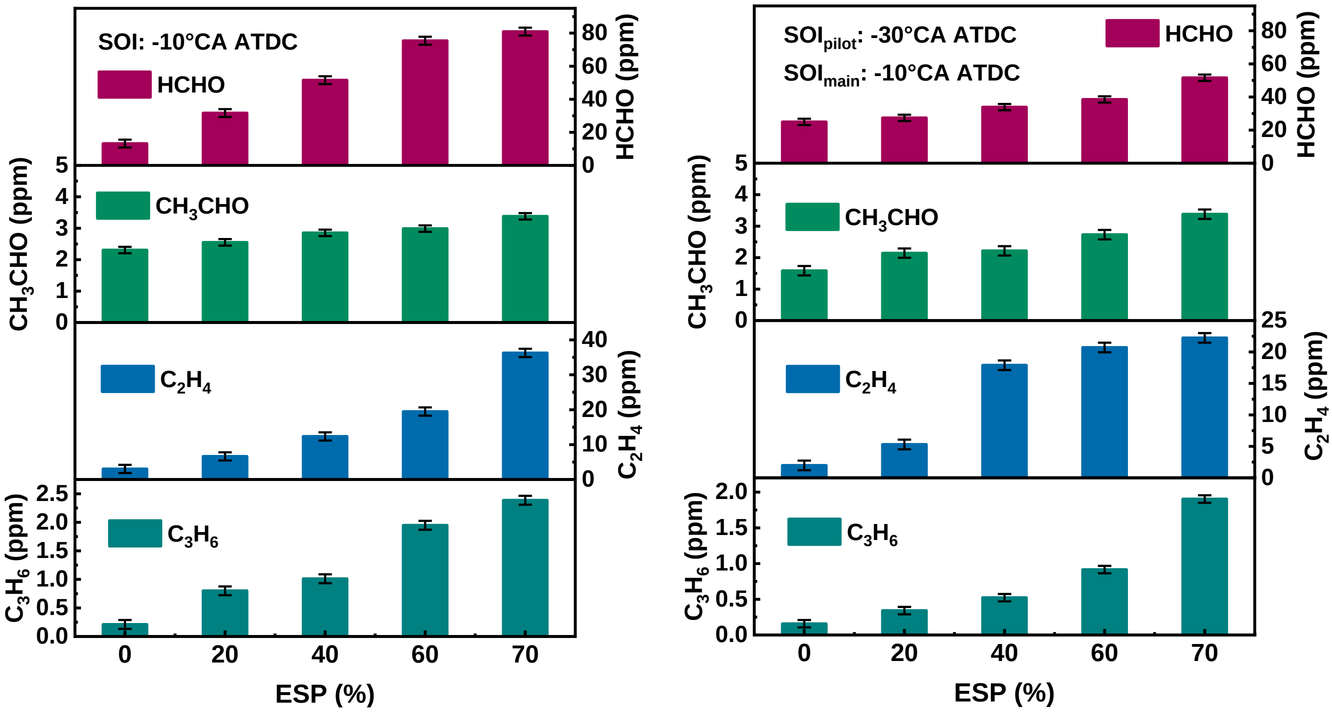


(a) Single injection

(b) Split injection

Fig. 6. Effects of ESP on NDDF engine NOx emissions at 25% load.

The influences of different ESP on NDDF engine unregulated emissions with two injection strategies at 25% load are presented in Fig. 7. It can be observed that the emissions of HCHO, CH_3CHO, C_2H_4 and C_3H_6 gradually increase with the increase of ESP under both strategies, but all maintain relatively low levels. Aldehydes, as the intermediate products of hydrocarbon oxidation, are generated by the incomplete combustion and low-temperature oxidation reaction of alcohols and hydrocarbon fuels during in-cylinder combustion process, and can mainly be observed in combustion chamber wall quenching layer. With the increase of ESP, the charging efficiency and the overall reactivity exhibited by the fuel in the cylinder decreases. In addition, the proportion of premixed natural gas increases and more premixed fuel enters the narrow gap. Because the overall temperature and pressure in the cylinder under low load are lower than the critical temperature and pressure ranges for HC oxidation, it is not conducive to the oxidation reaction, resulting in increased HCHO and CH_3CHO emissions. The emissions of C_2H_4 and C_3H_6 come from the low-temperature oxidation of in-cylinder fuel. As ESP elevates, the oxygen concentration in the cylinder lowers, the amount of oxygen atoms provided during combustion process decreases, the oxidation process of small olefin molecules is blocked, and some small olefin molecules are directly excluded from the cylinder without timely oxidation. Relative to single injection strategy, the pilot injection diesel is mixed in advance inside the cylinder under the split injection strategy, the reactivity of the mixture is enhanced, and a relatively ideal reactive stratification is formed in the cylinder (Fig. 7), which promotes the sufficient combustion of natural gas and finally makes the overall unregulated emissions lower.

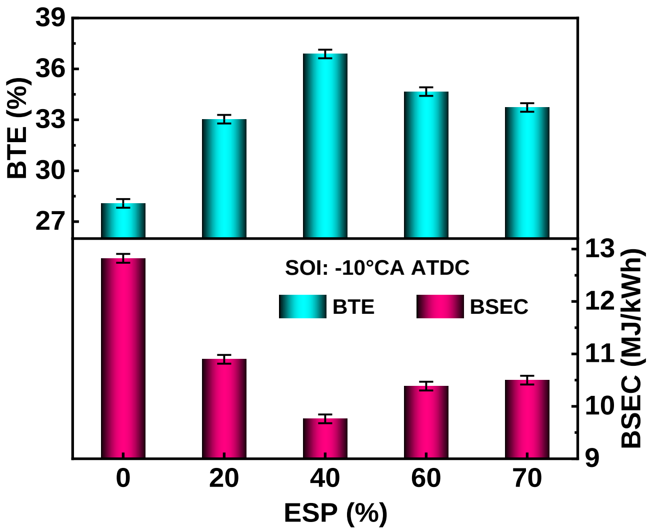


(a) Single injection (b) Split injection

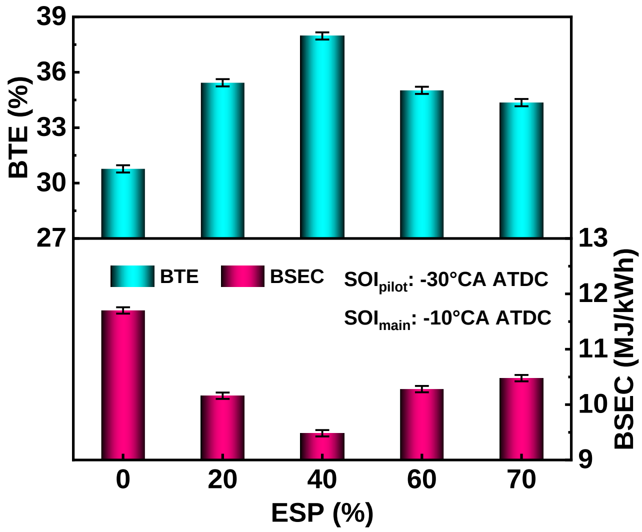
Fig. 7. Effects of ESP on NDDF engine unregulated emissions at 25% load.

3.1.3. Fuel economy

The influences of different ESP on BTE and BSEC regarding NDDF engine with two injection strategies at 25% load are indicated in Fig. 8. It can be found that under both strategies, BTE exhibits a trend of rising first and then declining as ESP increases. At 40% ESP, the BTE of the two injection strategies reach the maximum values of 36.88% and 37.97%, respectively. This is because when the natural gas with high heat capacity is injected into the cylinder through the intake port, the high turbulent motion in the combustion chamber improves the propagation speed of the flame front around the ignition area, and the amount of ignited diesel is larger at small ESP, the penetration distance is long, and the contact area with the mixture is large. The number of ignition sources for natural gas is large and the distribution is wide, so the combustion in the cylinder is more intense and the BTE is improved. When ESP continues to increase, the quantity of ignited diesel drops sharply, the overall reactivity of in-cylinder fuel decreases, and the CA50 is constantly delayed, so that more combustion occurs after TDC. The lean natural gas mixture outside the diesel spray can hardly support the propagation of the turbulent flame triggered by the trace diesel, and the premixed combustion rate of natural gas/air decreases, which intensifies incomplete combustion proportion and lowers the utilization rate of combustible mixture, therefore, the BTE of NDDF engine begins to gradually decrease. In addition, the higher ESP makes the injection duration of diesel fuel shorter, the penetration distance of diesel spray shorter and the ignition range smaller. The homogeneous mixture of ignited diesel is closer to the nozzle, the combustion rate slows down, and the intensity of diffusion combustion decreases, which also leads to BTE reduction. Relative to the single injection strategy, the BTE of each ESP under the split injection strategy is improved, as the application of split injection makes the CA05 and CA50 more advanced, increases the combustion constant volume, and significantly shortens the combustion duration.



(a) Single injection



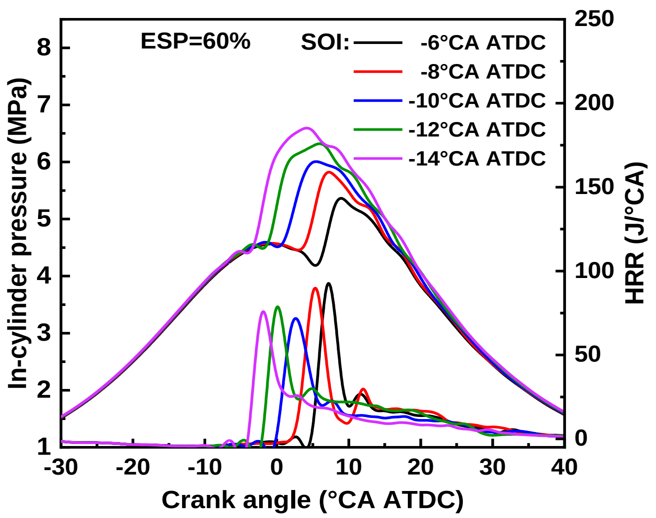
(b) Split injection

Fig. 8. Effects of ESP on NDDF engine fuel economy at 25% load.

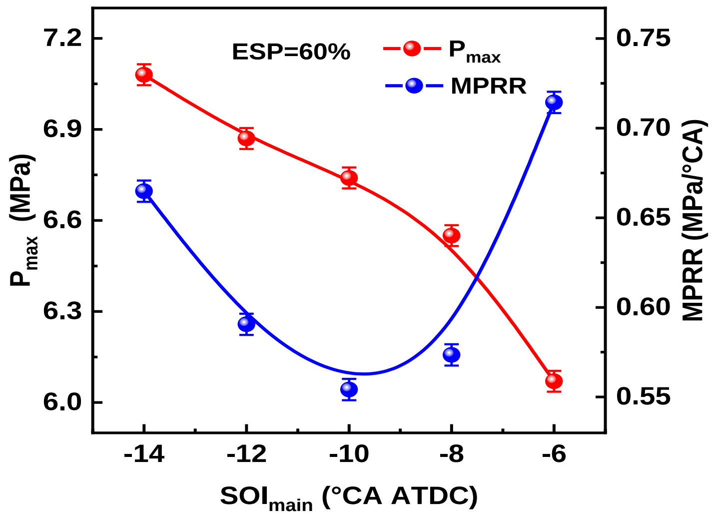
3.2 Influence of SOI_{main} on the performance of NDDF engine

3.2.1 Combustion characteristics

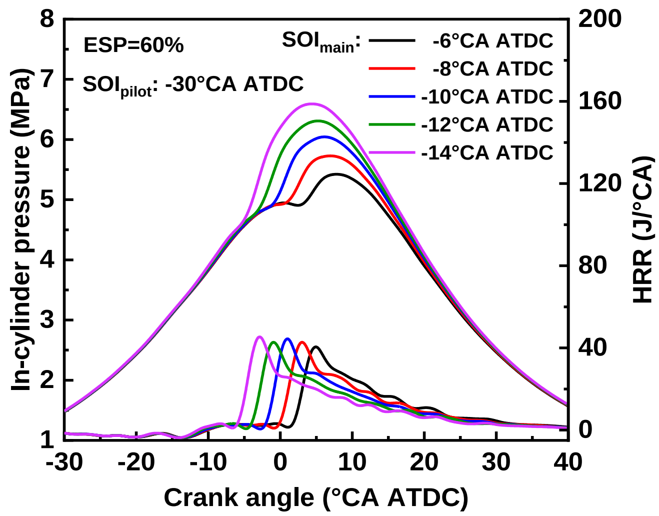
The influences of SOI_{main} on in-cylinder pressure and HRR regarding NDDF engine with two injection strategies at 60% ESP are displayed in Fig. 9. Under both injection strategies, as SOI_{main} advances, the P_{max} continues to rise, and the position where the in-cylinder pressure deviates from the compression curve also moves forward, which indicates the advance of the combustion heat release of NDDF. Affected by single injection strategy, the MPRR and peak HRR both present a decrease-to-increase trend. The amount of diesel injected near the TDC is more, the HRR is faster when combustion begins, and the double peak heat release phenomenon is more obvious. While the MPRR and peak HRR under the split injection strategy continue to rise. In addition, the MPRR of split injection strategy is smaller as a whole and does not exceed 0.45MPa/°CA. This is because more energy will be released during the compression stroke because of the advance of SOI_{main}, hence in-cylinder pressure and temperature become higher. When the SOI_{main} is too early, the MPRR in the cylinder keeps rising, and the in-cylinder combustion tends to be unstable. The advance of SOI_{main} makes the premixed fresh charge in the cylinder reach the ignition condition earlier, and the stratification degree of in-cylinder mixture is greatly reduced. At the same time, more and more diesel ignition cores are produced and distributed in the lean combustible mixture outside the diesel spray, which improves the reactivity of the combustible mixture and accelerates the combustion rate, and thus strengthening the initial combustion flame propagation speed of natural gas. Besides, the proportion of premixed combustion is increased, which makes the peak HRR increase continuously and the combustion heat release phase advance. With the SOI_{main} advanced to -14°CA ATDC, the peak HRR appears before the TDC. At this time, the compression work increases, and the phase of P_{max} deviates from the optimal region.



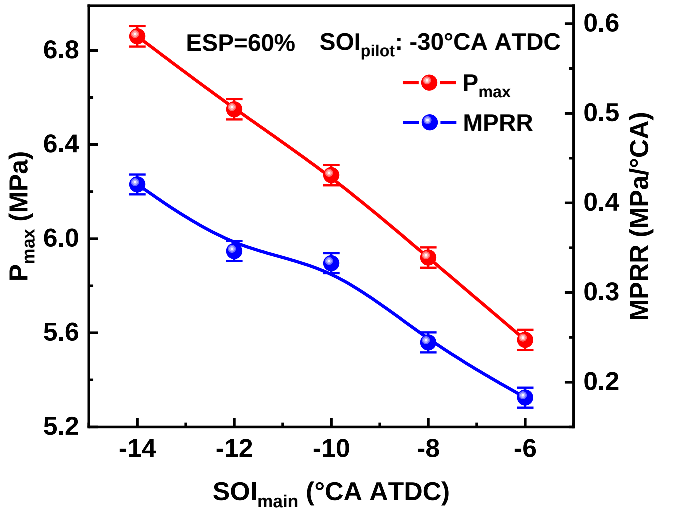
(a) In-cylinder combustion with single injection



(b) P_{max} and MPRR with single injection



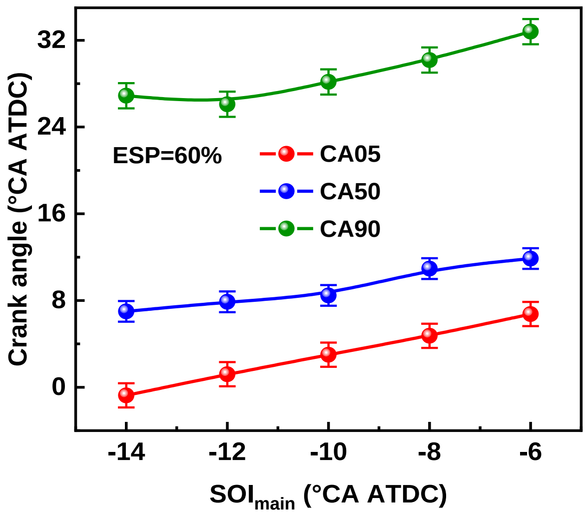
(c) In-cylinder combustion with split injection



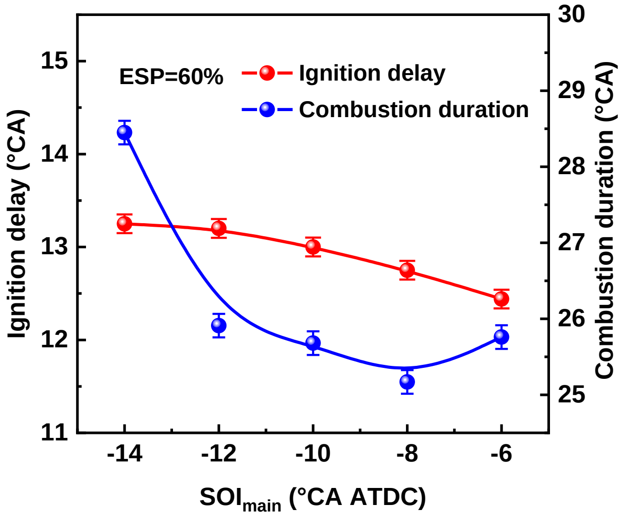
(d) P_{max} and MPRR with split injection

Fig. 9. Effects of SOI_{main} on in-cylinder pressure and HRR of NDDF engine at 25% load.

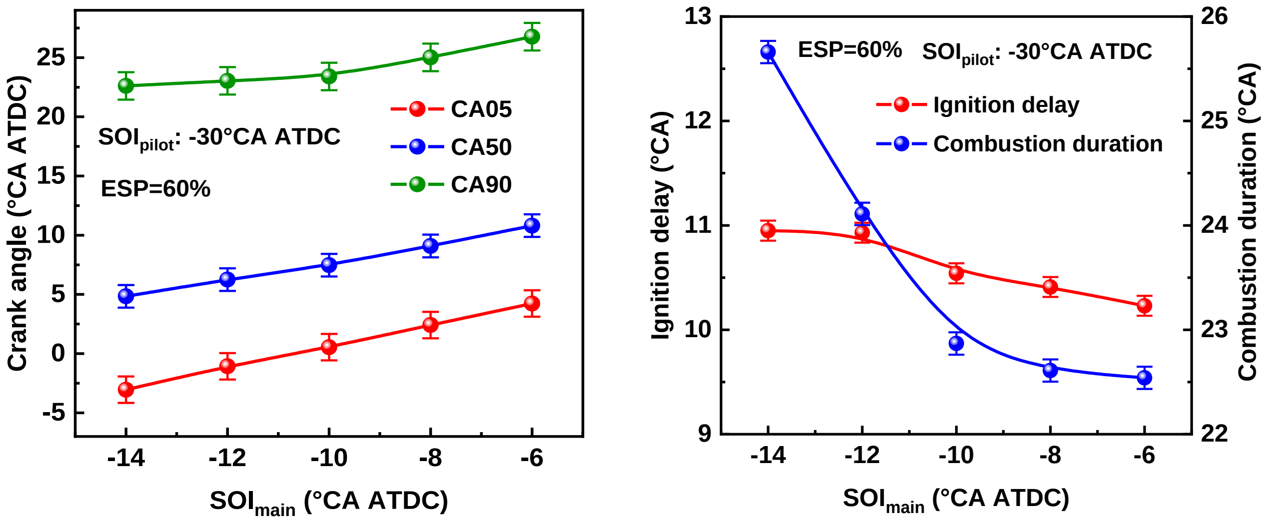
The way SOI_{main} affected the in-cylinder combustion process of NDDF engine with single and split injection strategies at 60% ESP are portrayed in Fig. 10. As shown in Fig. 10, under both injection strategies, as SOI_{main} advances, the phases of CA05, CA50 and CA90 continue to move forward, the CA50 gradually approaches the TDC, and the ignition delay period and combustion duration continue to extend. This is because with the advance of SOI_{main}, the lower compression pressure in the cylinder reduces the air resistance acting around the diesel spray, the diesel atomization quality becomes worse, and the physical preparation process of diesel before ignition is prolonged. In addition, the lower compression temperature decreases the chemical reaction rate of ignited diesel in the cylinder, which prolongs the chemical reaction process of the diesel before ignition, and extends the ignition delay period. The advance of SOI_{main} increases the ignition delay period meanwhile promoting a more homogeneous mixture to be formed in the cylinder (Liu et al., 2022), leading to an advanced combustion phase, enlarged ignition area and combustion speed, and increased combustion isovolumetric. Moreover, the CA05 and CA50 of split injection strategies are obviously advanced, and the CA90 is also advanced. The pilot injection diesel is premixed inside the cylinder in advance, which improves the mixture reactivity, forming a specific reactivity stratification. It makes the distribution range of combustible mixture wider, increases the ignition core and the ignition area of combustible mixture, which promotes the generation of thermal combustion products and activation groups. The combustible mixture combustion rate is accelerated, and ultimately the overall combustion phase is more advanced.



(a) Combustion phase with single injection



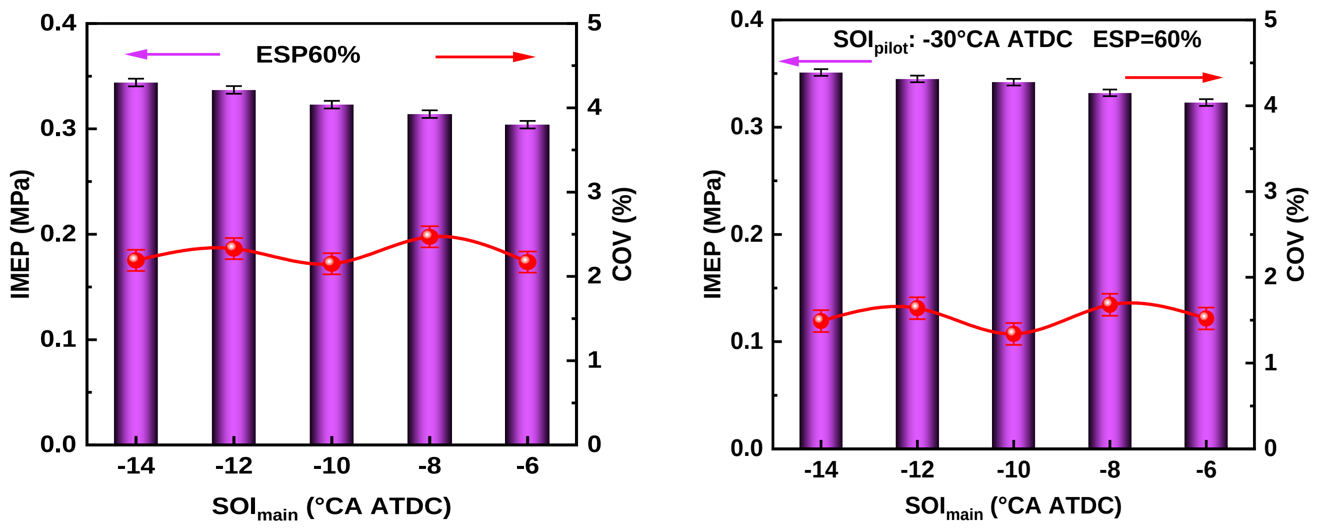
(b) Combustion stage with single injection



(c) Combustion phase with split injection (d) Combustion stage with split injection

Fig. 10. Effects of SOI_{main} on NDDF engine combustion process at 25% load.

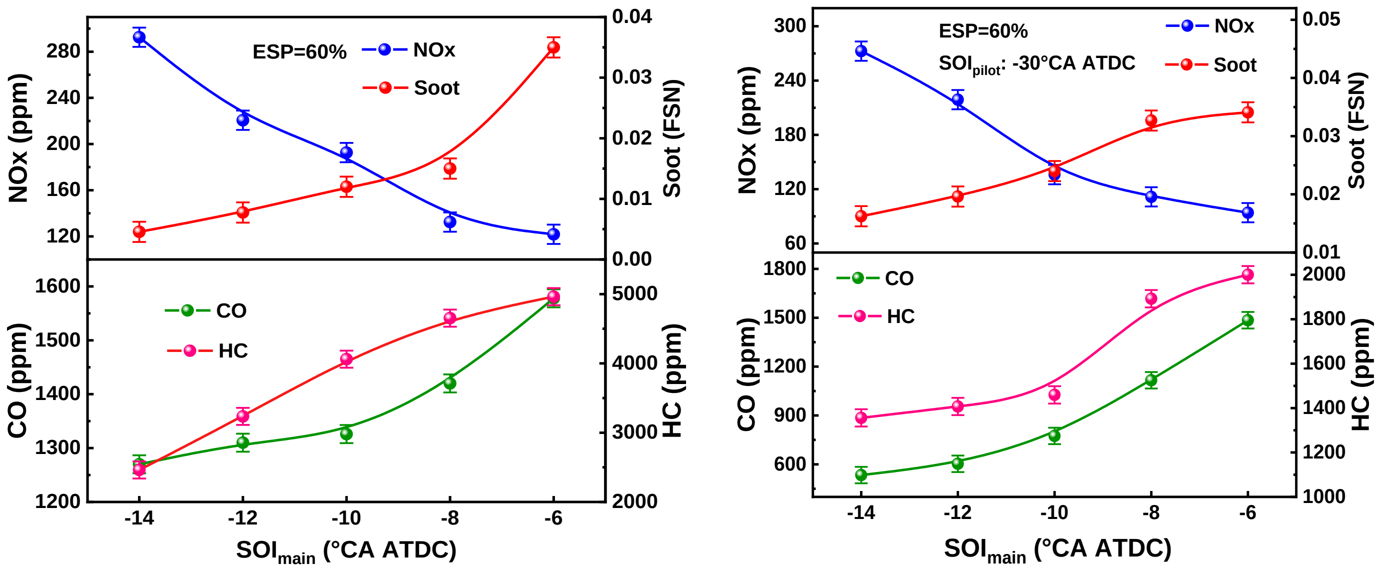
The influences of SOI_{main} on IMEP and COV of NDDF engine with two injection strategies at 60% ESP are shown in Fig. 11. As indicated in the figure, the IMEP exhibits an upward trend, while the COV fluctuates in a small range as SOI_{main} advances. In addition, the COV of split injection strategy is maintained at around 1.5%. This is because the injection timing of pilot injected diesel is early with split injection strategy, which will allow the natural gas/air mixture to be completely mixed before ignition, reducing the stratification degree of in-cylinder combustible mixture. The distribution of main injection diesel is more uniform, which broadens the ignition area of the mixture and enhances the overall combustion stability of NDDF engine. Furthermore, the earlier SOI_{pilot} slightly weakens the control of main injection diesel on the combustion start point, which is affected by the smaller cyclic variation of CA05. The COV of NDDF combustion is reduced, and there is a relatively steady in-cylinder combustion process.



(a) Single injection (b) Split injection

Fig. 11. Effects of SOI_{main} on IMEP and COV of NDDF engine at 25% load.

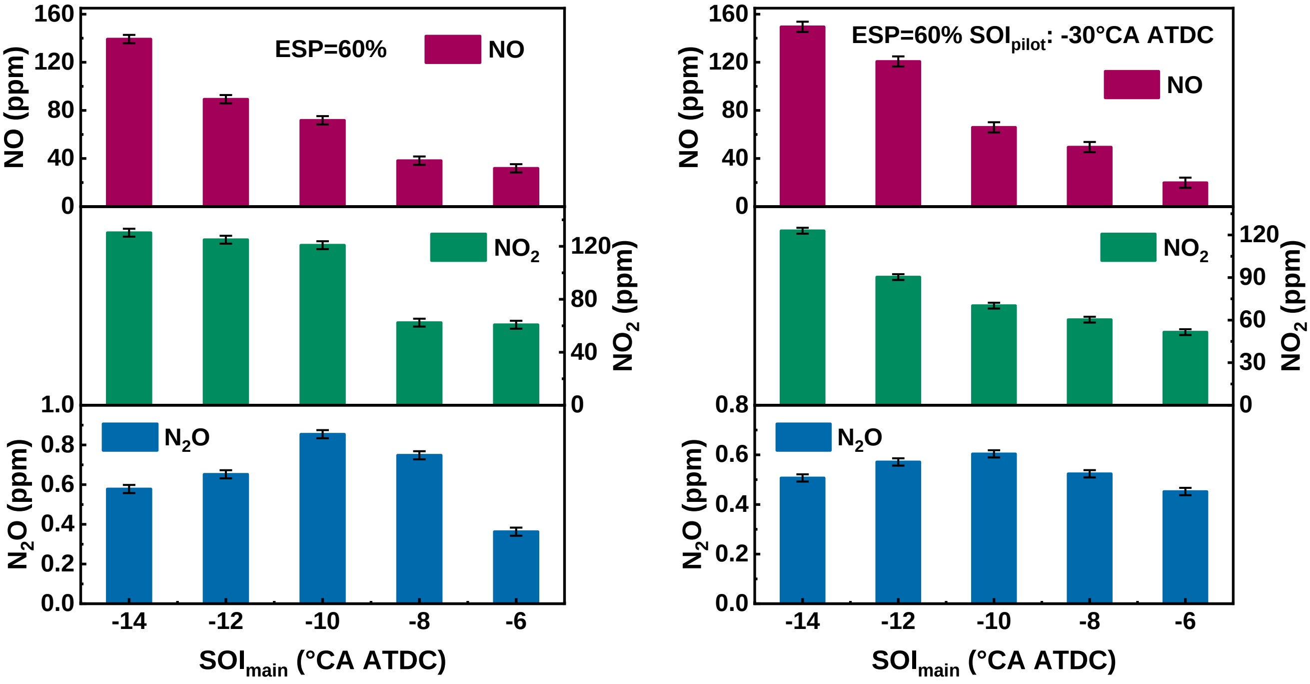
The influences of SOI_{main} on regulated emissions of NDDF engine with both injection strategies at 60% ESP are depicted in Fig. 12. Under both injection strategies, as SOI_{main} advances, the NOx emissions present an upward trend, but the soot, CO and HC emissions present a downward trend. In addition, the soot emission of split injection strategy is reduced by 10.67% at the SOI_{main} of -14°CA ATDC compared to the baseline engine. This is because the combustion start point of NDDF mode is mainly controlled by main injected diesel. As SOI_{main} advances, the CA05 and CA50 are continuously advanced and close to the TDC, so that more fuel is burned near the TDC. The continuous increase of in-cylinder temperature and pressure brings into a sharp rise in NOx emissions. In addition, the advance of SOI_{main} makes the ignited diesel enter the cylinder earlier, diesel and air mix more uniformly, the stratification degree of main injection diesel and combustible mixture in the cylinder decreases, the distribution range of main injection diesel in the mixture is wider, the local reactivity of the natural gas mixture is further enhanced, and the combustion rate of the mixture in the cylinder is accelerated, thereby reducing the probability of incomplete combustion. The advance of SOI_{main} improves the local over-concentration of the mixture during combustion process, and methane accounts for the majority of natural gas, which greatly reduces the production of soot precursors, and makes the overall soot emission at a lower level. When the SOI_{main} is advanced, ignited diesel and air mix more uniformly, the ignition is advanced, the natural gas combustion rate is accelerated, the pressure and temperature in the cylinder are increased, and the combustion of natural gas becomes more sufficient, resulting in a decrease in CO and HC emissions.



(a) Single injection (b) Split injection

Fig. 12. Effects of SOI_{main} on NDDF engine regulated emissions at 25% load.

The influences of SOI_{main} on NOx emissions of NDDF engine with both injection strategies at 60% ESP are displayed in Fig. 13. Under both injection strategies, as SOI_{main} advances, NO and NO_2 emissions present an upward trend, while N_2O emission first increases and then decreases, and NO emission of split injection strategy is reduced by 12.27% when SOI_{main} is -14°CA ATDC compared to baseline engine. This is because the SOI_{main} significantly controls the in-cylinder combustion process. Due to the advanced SOI_{main}, the combustion pressure and temperature in the cylinder rise, the amount of premixed combustion increases, the mixture combustion rate accelerates, and the local high-temperature area increases, which provides the conditions for NO formation, causing NO emission to increase remarkably. Moreover, the overall combustion duration and high-temperature duration in the cylinder are relatively long, and the conversion rate of NO to NO_2 is accelerated, which eventually leads to the increase of NO_2 emission. When the SOI_{main} is gradually advanced, the in-cylinder combustion temperature and pressure are relatively low, and the content of reducing substances such as CO and HC is high, which is conducive to N_2O formation. When the SOI_{main} continues to advance, the two indexes in the cylinder increase continuously, which promotes the conversion of N_2O to NO and N_2 by virtue of N_2O + O=2NO and N_2O (+M)=N_2 + O (+M) reactions. When the SOI_{main} is relatively early, the amount of reducing substances in the cylinder decreases, which suppresses the reaction of partial NO being reduced to N_2O, resulting in a decrease in N_2O emission.

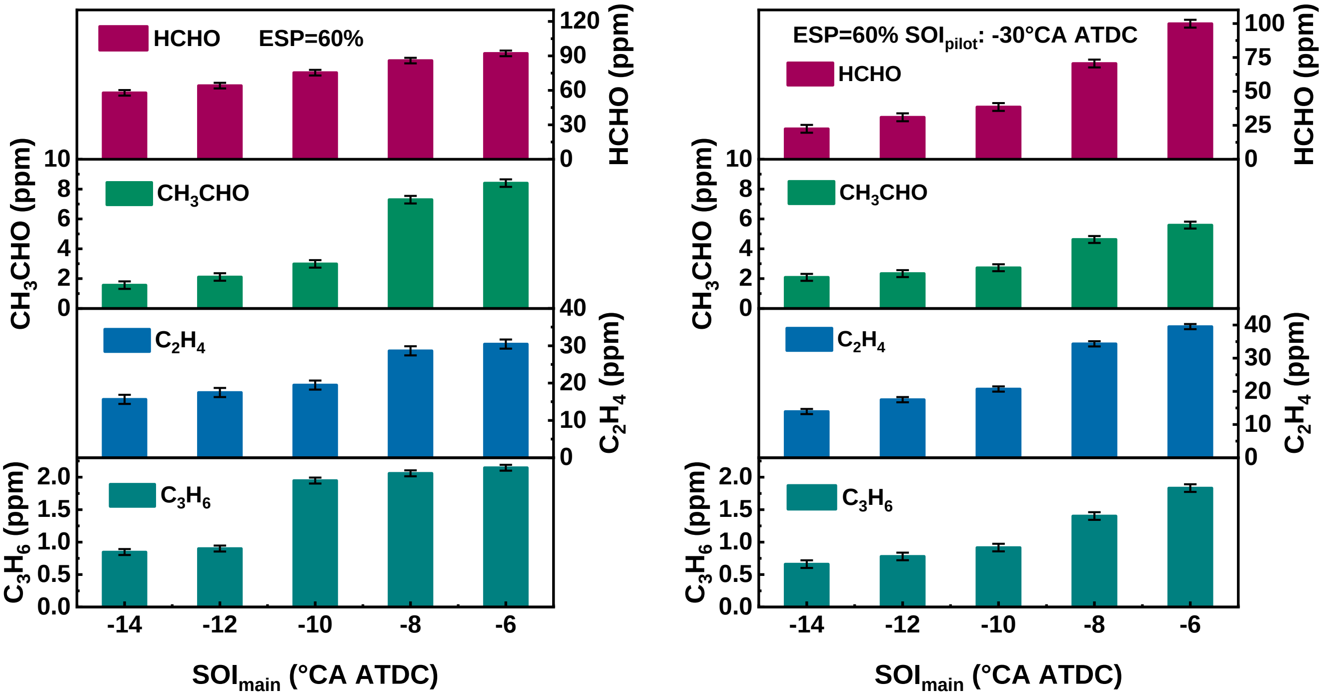


(a) Single injection (b) Split injection

Fig. 13. Effects of SOI_{main} on NDDF engine NOx emissions at 25% load.

The influences of SOI_{main} on unregulated emissions regarding NDDF engine with both injection strategies at 60% ESP are given in Fig. 14. Under both injection strategies, the emissions of HCHO, CH_3CHO, C_2H_4 and C_3H_6 all exhibit a downward trend with the advance of SOI_{main}, and the overall emissions remain at a relatively low level. The advance of SOI_{main} makes more fuel burn near the TDC, and when temperature and pressure become higher in the cylinder, the oxidation reaction of HCHO and CH_3CHO is strengthened. Meanwhile, as ignition delay period elevates, the stratification degree of the in-cylinder mixture decreases, the reactivity of natural gas mixture increases, and the HRR of combustible mixture enhances, thereby enhancing the combustion efficiency as well as inhibiting the production of C_2H_4

and C_3H_6 in the cylinder. Additionally, the pilot injected diesel is mixed in advance in the cylinder with split injection, which reduces the in-cylinder reactivity stratification of diesel and mixture, enhances the reaction activity of the mixture outside the diesel spray, widens the combustion boundary of the combustible mixture in the diesel spray, improves the combustion perfection of natural gas, and finally makes the overall unregulated emissions decrease.

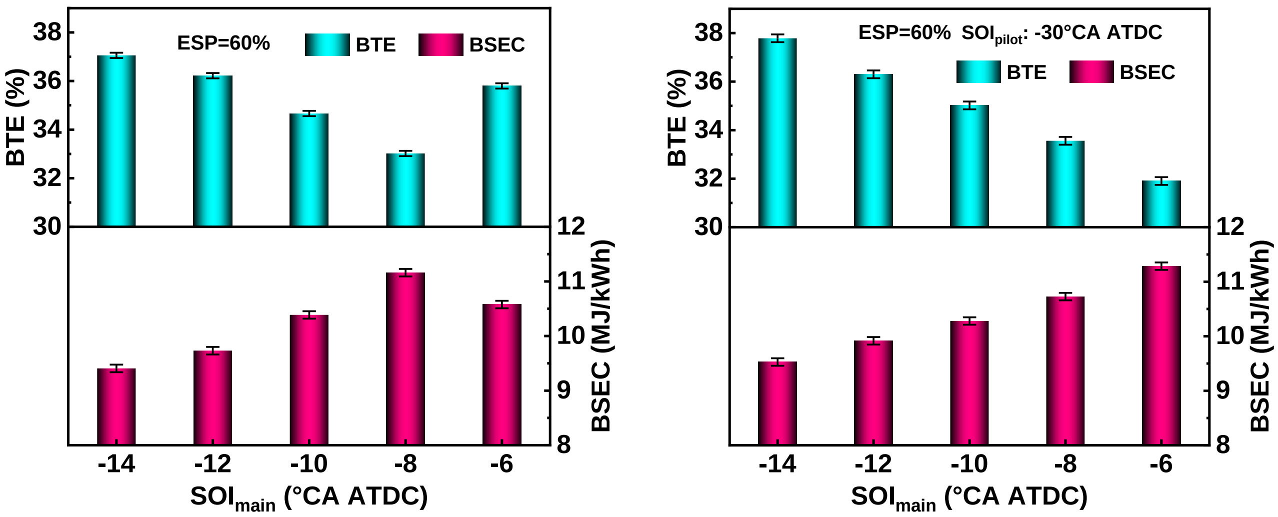


(a) Single injection (b) Split injection

Fig. 14. Effects of SOI_{main} on NDDF engine unregulated emissions at 25% load.

3.2.3. Fuel economy

The influences of SOI_{main} on BTE and BSFC of NDDF engine with both injection strategies at 60% ESP are illustrated in Fig. 15. It is found that under both strategies, as SOI_{main} is on an advance, the BTE increases, but BSEC decreases slowly. With the SOI_{main} at -14°CA ATDC, the maximum BTE values of 37.06% and 37.79% are obtained, respectively, because the earlier the ignited diesel is injected into the cylinder, the more sufficient time to uniformly mix with the air, and more uniform mixture is formed. Meanwhile, the ignition time is advanced, the CA50 is also moved forward, the amount of ignition cores is increased, and the distribution range is wider, which accelerates the initial combustion flame propagation speed of natural gas, the premixed combustion rate of diesel is accelerated, and the combustion isovolumetric degree becomes larger, which ultimately makes the fuel economy of NDDF engine improve. When the SOI_{main} continues to advance, the P_{max} and MPRR continue to increase, the COV fluctuates substantially, NOx emissions rise sharply, and the combustion instability of NDDF engine increases sharply.



(a) Single injection

(b) Split injection

Fig. 15. Effects of SOI_{main} on NDDF engine fuel economy at 25% load.

4. Conclusions

In the present research, the NDDF combustion mode was operated on a high-pressure common-rail agricultural diesel engine, and how ESP and SOI_{main} impacted the in-cylinder combustion and emission properties exhibited by the NDDF engine under single injection and split injection strategies at 25% load were studied through comparative tests. The study mainly contributes to four findings:

(1) Under single injection and split injection strategies, as ESP elevated, the P_{max} presented a decrease-to-increase change trend, the HRR curve of NDDF mode slowly evolved from single-stage to two-stage, the CA50 moved backward, the combustion duration increased, while the BTE presented an increase-to-decrease change trend. The CA05, CA50 and CA90 of the split injection strategy moved forward as a whole, the ignition delay period was shortened, the COV was reduced, and BTE was significantly increased relative to the single injection. At 40% ESP, the BTE could reach the maximum value of 37.97%.

(2) Under both injection strategies, as ESP was on a rise, the NOx emissions first increased and then decreased, the soot and NO emissions became less, and the emissions of HC, CO, NO_2, HCHO, CH_3CHO, C_2H_4 and C_3H_6 increased to a certain extent. Under the split injection strategy, relatively to baseline engine, the emissions of soot and NO decreased by 29.63% and 69.31% at 70% ESP, respectively.

(3) As SOI_{main} advanced, the P_{max} of NDDF engine slowly increased, the combustion heat release process was gradually advanced, the positions of CA05, CA50 and CA90 were continuously advanced, the ignition delay period as well as combustion duration were extended, and the BTE also gradually increased. Relative to diesel single injection, the MPRR and peak HRR of the split injection gradually increased, and the COV remained around 1.5%.

(4) Under both injection strategies, the NOx emissions of NDDF engine increased as SOI_{main} advanced, while the emissions of soot, HC, CO, HCHO, CH_3CHO, C_2H_4 and C_3H_6 all decreased. Compared with baseline engine, the NO and soot emissions decreased by 12.27% and 10.67%, respectively, and the maximum BTE of 37.79% was obtained at the split injection and 60% ESP conditions.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 51806086), and the Special Project of Ministry of Agriculture and Rural Affairs of China (No. NK20221601).

References

Agarwal, A.K., Singh, A.P., Maurya, R.K., 2017. Evolution, challenges and path forward for low temperature combustion engines. Prog. Energy Combust. Sci. 61, 1-56. https://doi.org/10.1016/j.pecs.2017.02.001.

Asad, U., Zheng, M., 2014. Exhaust gas recirculation for advanced diesel combustion cycles. Appl. Energy 123, 242-252. https://doi.org/10.1016/j.apenergy.2014.02.073.

Bayramoğlu, K., Özmen, G., 2021. Design and performance evaluation of low-speed marine diesel engine selective catalytic reduction system. Process Saf. Environ. Prot. 155, 184-196. https://doi.org/10.1016/j.psep.2021.09.010.

Chen, H., Su, X., He, J., Xie, B., 2019. Investigation on combustion and emission characteristics of a common rail diesel engine fueled with diesel/n-pentanol/methanol blends. Energy 167, 297-311. https://doi.org/10.1016/j.energy.2018.10.199.

Chen, Z., He, J., Chen, H., Geng, L., Zhang, P., 2021. Experimental study on cycle-to-cycle variations in natural gas/methanol bi-fueled engine under excess air/fuel ratio at 1.6. Energy 224, 120233. https://doi.org/10.1016/j.energy.2021.120233.

Duan, H., Jia, M., Li, Y., Wang, T., 2021. A comparative study on the performance of partially premixed combustion (PPC), reactivity-controlled compression ignition (RCCI), and RCCI with reverse reactivity stratification (R-RCCI) fueled with gasoline and polyoxymethylene dimethyl ethers (PODEn). Fuel 298, 120838. https://doi.org/10.1016/j.fuel.2021.120838.

Field, R.A., Derwent, R.G., 2021. Global warming consequences of replacing natural gas with hydrogen in the domestic energy sectors of future low-carbon economies in the United Kingdom and the United States of America. Int. J. Hydrog. Energy 46, 30190-30203. https://doi.org/10.1016/j.ijhydene.2021.06.120.

Gholami, A., Jazayeri, S.A., Esmaili, Q., 2022. A detail performance and CO_2 emission analysis of a very large crude carrier propulsion system with the main engine running on dual fuel mode using hydrogen/diesel versus natural gas/diesel and conventional diesel engines. Process Saf. Environ. Prot. 163, 621-635. https://doi.org/10.1016/j.psep.2022.05.069.

Gong, Z., Feng, L., Wei, L., Qu, W., Li, L., 2020. Shock tube and kinetic study on ignition characteristics of lean methane/n-heptane mixtures at low and elevated pressures. Energy 197, 117242. https://doi.org/10.1016/j.energy.2020.117242.

Hernández, J.J., Lapuerta, M., Barba, J., 2016. Separate effect of H_2, CH_4 and CO on diesel engine performance and emissions under partial diesel fuel replacement. Fuel 165, 173-184. https://doi.org/10.1016/j.fuel.2015.10.054.

~~Huang, H., Liu, Q., Teng, W., Pan, M., Liu, C., Wang, Q., 2018. Improvement of combustion performance and emissions in diesel engines by fueling n-butanol/diesel/$PODE_{3-4}$ mixtures. Appl. Energy 227, 38-48. https://doi.org/10.1016/j.apenergy.2017.09.088.~~

Huang, H., Zhu, Z., Chen, Y., Chen, Y., Lv, D., Zhu, J., Ouyang, T., 2019. Experimental and numerical study of multiple injection effects on combustion and emission characteristics of natural gas–diesel dual-fuel engine. Energ. Convers. Manage. 183, 84-96. https://doi.org/10.1016/j.enconman.2018.12.110.

Jain, A., Singh, A.P., Agarwal, A.K., 2017. Effect of split fuel injection and EGR on NOx and PM emission reduction in a low temperature combustion (LTC) mode diesel engine. Energy 122, 249-264. https://doi.org/10.1016/j.energy.2017.01.050.

Johnson, D.R., Heltzel, R., Nix, A.C., Clark, N., Darzi, M., 2017. Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development. Appl. Energy 206, 739-750. https://doi.org/10.1016/j.apenergy.2017.08.234.

Koç, M.A., Şener, R., 2021. Prediction of emission and performance characteristics of reactivity-controlled compression ignition engine with the intelligent software based on adaptive neural-fuzzy and neural-network. J. Clean. Prod. 318, 128642. https://doi.org/10.1016/j.jclepro.2021.128642.

Lee, C.f., Pang, Y., Wu, H., Nithyanandan, K., Liu, F., 2020. An optical investigation of substitution rates on natural gas/diesel dual-fuel combustion in a diesel engine. Appl. Energy 261, 114455. https://doi.org/10.1016/j.apenergy.2019.114455.

Li, T., Zhou, X., Wang, N., Wang, X., Chen, R., Li, S., Yi, P., 2022. A comparison between low- and high-pressure injection dual-fuel modes of diesel-pilot-ignition ammonia combustion engines. J. Energy Inst. 102, 362-373. https://doi.org/10.1016/j.joei.2022.04.009.

Li, Y., Cao, Z., Chen, Y., Wu, G., 2021. A synthetic skeletal mechanism for combustion simulation of acetone-n-butanol-ethanol mixture and its components in diesel engines. Fuel 290, 120097. https://doi.org/10.1016/j.fuel.2020.120097.

Li, Y., Chen, Y., Wu, G., Lee, C.-f.F., Liu, J., 2018a. Experimental comparison of acetone-n-butanol-ethanol (ABE) and isopropanol-n-butanol-ethanol (IBE) as fuel candidate in spark-ignition engine. Appl. Therm. Eng. 133, 179-187. https://doi.org/10.1016/j.applthermaleng.2017.12.132.

Li, Y., Chen, Y., Wu, G., Liu, J., 2018b. Experimental evaluation of water-containing isopropanol-n-butanol-ethanol and gasoline blend as a fuel candidate in spark-ignition engine. Appl. Energy 219, 42-52. https://doi.org/10.1016/j.apenergy.2018.03.051.

Li, Y., Li, H., Guo, H., Li, Y., Yao, M., 2017. A numerical investigation on methane combustion and emissions from a natural gas-diesel dual fuel engine using CFD model. Appl. Energy 205, 153-162. https://doi.org/10.1016/j.apenergy.2017.07.071.

Liang, J., Zhang, Z., Li, G., Wan, Q., Xu, L., Fan, S., 2019. Experimental and kinetic studies of ignition processes of the methane–n-heptane mixtures. Fuel 235, 522-529. https://doi.org/10.1016/j.fuel.2018.08.041.

Liu, J., Wu, P., Ji, Q., Sun, P., Wang, P., Meng, Z., Ma, H., 2022. Experimental study on effects of pilot injection strategy on combustion and emission characteristics of diesel/methanol dual-fuel engine under low load. Energy 247, 123464. https://doi.org/10.1016/j.energy.2022.123464.

Liu, Z., Zhou, L., Liu, B., Zhao, W., Wei, H., 2019. Effects of equivalence ratio and pilot fuel mass on ignition/extinction and pressure oscillation in a methane/diesel engine with pre-chamber. Appl. Therm. Eng. 158, 113777. https://doi.org/10.1016/j.applthermaleng.2019.113777.

Ma, S., Zheng, Z., Liu, H., Zhang, Q., Yao, M., 2013. Experimental investigation of the effects of diesel injection strategy on gasoline/diesel dual-fuel combustion. Appl. Energy 109, 202-212. https://doi.org/10.1016/j.apenergy.2013.04.012.

Musculus, M.P.B., Miles, P.C., Pickett, L.M., 2013. Conceptual models for partially premixed low-temperature diesel combustion. Prog. Energy Combust. 39, 246-283. https://doi.org/10.1016/j.pecs.2012.09.001.

Navarro, E., Leo, T.J., Corral, R., 2013. CO_2 emissions from a spark ignition engine operating on natural gas–hydrogen blends (HCNG). Appl. Energy 101, 112-120. https://doi.org/10.1016/j.apenergy.2012.02.046.

Niklawy, W., Shahin, M., Amin, M.I., Elmaihy, A., 2022. Comprehensive analysis of combustion phasing of multi-injection HCCI diesel engine at different speeds and loads. Fuel 314, 123083. https://doi.org/10.1016/j.fuel.2021.123083.

Ouchikh, S., Lounici, M.S., Loubar, K., Tarabet, L., Tazerout, M., 2022. Effect of diesel injection strategy on performance and emissions of CH4/diesel dual-fuel engine. Fuel 308, 121911. https://doi.org/10.1016/j.fuel.2021.121911.

Pandey, S.K., Sarma Akella, S.R., Ravikrishna, R.V., 2018. Novel fuel injection strategies for PCCI operation of a heavy-duty turbocharged diesel engine. Appl. Therm. Eng. 143, 883-898. https://doi.org/10.1016/j.applthermaleng.2018.08.001.

Park, H., Shim, E., Bae, C., 2019. Expansion of low-load operating range by mixture stratification in a natural gas-diesel dual-fuel premixed charge compression ignition engine. Energ. Convers. Manage. 194, 186-198. https://doi.org/10.1016/j.enconman.2019.04.085.

Poorghasemi, K., Saray, R.K., Ansari, E., Irdmousa, B.K., Shahbakhti, M., Naber, J.D., 2017. Effect of diesel injection strategies on natural gas/diesel RCCI combustion characteristics in a light duty diesel engine. Appl. Energy 199, 430-446. https://doi.org/10.1016/j.apenergy.2017.05.011.

~~Raza, M., Chen, L., Ruiz, R., Chu, H., 2019. Influence of pentanol and dimethyl ether blending with diesel on the combustion performance and emission characteristics in a compression ignition engine under low temperature combustion mode. J. Energy Inst. 92, 1658-1669. https://doi.org/10.1016/j.joei.2019.01.008.~~

Reitz, R.D., Duraisamy, G., 2015. Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. Prog. Energy Combust. Sci. 46, 12-71. https://doi.org/10.1016/j.pecs.2014.05.003.

Ren, Y., Lou, D., Tan, P., Zhang, Y., Sun, X., 2021. Emission reduction characteristics of after-treatment system on natural gas engine: Effects of platinum group metal loadings and ratios. J. Clean. Prod. 298, 126833. https://doi.org/10.1016/j.jclepro.2021.126833.

Salahi, M.M., Gharehghani, A., 2019. Control of combustion phasing and operating range extension of natural gas PCCI engines using ozone species. Energ. Convers. Manage. 199, 112000. https://doi.org/10.1016/j.enconman.2019.112000.

Sharma, H., Dhir, A., Mahla, S.K., 2021. Application of clean gaseous fuels in compression ignition engine under dual fuel mode: A technical review and Indian perspective. J. Clean. Prod. 314, 128052. https://doi.org/10.1016/j.jclepro.2021.128052.

Singh, E., Morganti, K., Dibble, R., 2019. Dual-fuel operation of gasoline and natural gas in a turbocharged engine. Fuel 237, 694-706. https://doi.org/10.1016/j.fuel.2018.09.158.

Splitter, D., Hanson, R., Kokjohn, S., Wissink, M., Reitz, R.D., 2011. Injection Effects in Low Load RCCI Dual-Fuel Combustion. SAE Paper 2011. https://doi.org/10.4271/2011-24-0047.

Wang, Z., Fu, X., Wang, D., Xu, Y., Du, G., You, J., 2021. A multilevel study on the influence of natural gas substitution rate on combustion mode and cyclic variation in a diesel/natural gas dual fuel engine. Fuel 294, 120499. https://doi.org/10.1016/j.fuel.2021.120499.

Wei, J., He, C., Lv, G., Zhuang, Y., Qian, Y., Pan, S., 2021. The combustion, performance and emissions investigation of a dual-fuel diesel engine using silicon dioxide nanoparticle additives to methanol. Energy 230, 120734. https://doi.org/10.1016/j.energy.2021.120734.

Wei, L., Yao, C., Wang, Q., Pan, W., Han, G., 2015. Combustion and emission characteristics of a turbocharged diesel engine using high premixed ratio of methanol and diesel fuel. Fuel 140, 156-163. https://doi.org/10.1016/j.fuel.2014.09.070.

Wen, M., Liu, H., Cui, Y., Ming, Z., Feng, L., Yao, M., 2023. Optical diagnostics of methanol active-thermal atmosphere combustion in compression ignition engine. Fuel 332, 126036. https://doi.org/10.1016/j.fuel.2022.126036.

Wu, S., Bao, J., Wang, Z., Zhang, H., Xiao, R., 2021. The regulated emissions and PAH emissions of bio-based long-chain ethers in a diesel engine. Fuel Process. Technol. 214, 106724. https://doi.org/10.1016/j.fuproc.2021.106724.

Yousefi, A., Birouk, M., 2017. Investigation of natural gas energy fraction and injection timing on the performance and emissions of a dual-fuel engine with pre-combustion chamber under low engine load. Appl. Energy 189, 492-505. https://doi.org/10.1016/j.apenergy.2016.12.046.

Yousefi, A., Guo, H., Birouk, M., 2018. Effect of swirl ratio on NG/diesel dual-fuel combustion at low to high engine load conditions. Appl. Energy 229, 375-388. https://doi.org/10.1016/j.apenergy.2018.08.017.

Zhou, D., Yang, W., Zhao, F., Li, J., 2017. Dual-fuel RCCI engine combustion modeling with detailed chemistry considering flame propagation in partially premixed combustion. Appl. Energy 203, 164-176. https://doi.org/10.1016/j.apenergy.2017.06.021.

Zhu, Z., Li, Y., Shi, C., 2022. Effect of natural gas energy fractions on combustion performance and emission characteristics in an optical CI engine fueled with natural gas/diesel dual-fuel. Fuel 307, 121842. https://doi.org/10.1016/j.fuel.2021.121842.