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# Effects of natural gas injection timing and split pilot fuel injection strategy on the combustion performance and emissions in a dual-fuel engine fueled with diesel and natural gas

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ABSTRACT

Considering the drawbacks of a diesel/natural gas dual-fuel combustion at low load usually is relative to undesirable natural gas-air-diesel mixture distributions in-cylinder and natural gas supply method and pilot diesel injection strategy are believed to play a critical role in the process of mixture formation in the cylinder. So an experimental study has been conducted to explore the effects of natural gas injection timing and split pilot injection strategy on the combustion performance and emissions characteristics in a diesel/natural gas dual-fuel engine.

In this study, the effects of natural gas injection timing under a constant split pilot injection strategy and a varying first pilot injection timing under an optimized natural gas injection timing on combustion performance and emissions are evaluated. The cylinder pressure, Heat Release Rate (HRR), Pressure Rise Rate (PRR), ignition delay, flame development duration, CA50 and combustion duration as well as THC, CO, $NO_x$ emissions are analyzed for the purpose.

The experimental results indicated that natural gas injection timing and split injection strategy have a significant influence on the combustion performance and emissions characteristics in the dual-fuel engine. The natural gas premixed combustion stage can be enhanced with retarded natural gas injection timing. The pilot diesel combustion stage is weakened under the split injection strategy and the combustion process can be improved by reasonably advanced first pilot injection timing. Moreover, combined variation natural gas injection timing and split pilot injection strategy is a potential way to optimize the performance of the diesel/natural gas dual-fuel engine.

## 1. Introduction

With increasing concerns about the air pollution and the depletion of global oil reserves, in recent years, researchers are trying to find a solution to improve the traditional internal combustion engine in order to realize a more efficiency and cleaner combustion. For this purpose, the Low-Temperature Combustion (LTC) theory had been proposed and is generally regarded as one of the promising theories to guide improving the performance of the traditional diesel engines [1,2]. The dual-fuel operation strategy is a typical method to achieve the LTC in the traditional internal combustion engines and a lot of studies had confirmed that the $NO_x$ and PM emissions in a diesel engine can be simultaneously reduced under the dual-fuel operation strategy [3,4]. As a result, the dual-fuel combustion strategy has caught numerous attentions all over the world and researchers present various concepts of the dual-fuel engines, such as pilot ignited [5,6] and reactivity controlled compression ignition (RCCI) [7,8]. A lot of gaseous fuels were seriously evaluated in the dual-fuel combustion engine this before and natural gas is believed as one of the most suitable alternative fuels applied in the dual-fuel combustion engine due to the wide distribution all over the world, low price compared with conventional fossil fuel and clean burning as well as a good antiknock property [9,10].

In recent years, extensive investigations have been conducted to explore the combustion performance and emissions in diesel/natural gas dual-fuel engines all over the world [11,5]. The effects of various operation parameters on diesel/natural gas dual-fuel engine had been experimental and simulation investigated. For example, the pilot injection timing and pressure [12,13], the substitution rate [14], and natural gas supply method [15] as well as engine operation parameters (speed, load, etc.) [16,17]. Those investigations had confirmed that the diesel/natural gas dual-fuel combustion strategy is one of the most promising methods to realize the high efficiency and low emissions

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**Nomenclature**

| | |
|---|---|
| TDC | top dead center |
| ATDC | after top dead center |
| ABDC | after bottom dead center |
| BTDC | before top dead center |
| BBDC | before bottom dead center |
| CA | crank angle |
| BMEP | brake mean effective pressure |
| ECU | electronic control unit |
| HRR | heat release rate |
| RCCI | reactivity controlled compression ignition |
| CO | nitric oxide |
| $NO_x$ | nitrogen oxides |
| THC | total hydrocarbon |
| PRR | pressure raise rate |
| LTC | low temperature combustion |
| PREMIER | premixed mixture ignition in the end gas region |
| CA50 | crank angle at 50% mass fraction burned |
| CNG | compressed natural gas |

combustion in a diesel engine. However, there are still some drawbacks under the dual-fuel combustion mode and need to overcome, such as the unstable combustion performance and higher unburned $CH_4$ emissions under low and medium loads [18].

The previous studies mentioned above indicated that the spatial distributions of natural gas and pilot fuel in cylinder play a critical role in the ignition kernel formation and flame development. Moreover, the thermal and kinetic interaction inside a mixture in cylinder is believed significantly influencing a dual-fuel combustion performance and emissions characteristics. The drawbacks mentioned above are mainly due to inappropriate natural gas-air-diesel mixture distributions in cylinder [15,16]. As a result, some researchers try to improve the mixing process of natural gas and diesel in the cylinder in order to optimize the performance of dual-fuel combustion engines. So the split pilot fuel injection and natural gas port injection strategies have been investigated recently. For example, Yousefi et al. [19,20] developed a multidimensional Computational Fluid Dynamics (CFD) model to explore the different pilot fuel injection strategies in a dual-fuel combustion engine under low load. They compared the effects of single, double and triple pilot fuel injection strategies under the same operating condition. Their studies showed that the pilot fuel injection strategies have a significant influence on the combustion and emissions of a dual-fuel engine. Cagdas Aksu et al. [21] employed the split micro pilot fuel injection strategy to extend the PREMIER (PREmixed Mixture Ignition in the End Gas Region) combustion operation range in a dual-fuel engine and they reported that the PREMIER combustion has been achieved in a wide range under the split pilot fuel injection strategy in an experimental study. Their investigation indicated that the size and rate of growth of flame kernels were obviously influenced by the timing of the second injection. Carlucci AP et al. [15] explore the effects of methane supply method combined with variable in-cylinder charge bulk motion on a diesel/natural gas dual-fuel combustion and emissions. They believed that some stratification of the mixture was obtained by varying the methane supply method combined charge bulk motion. And the stratification will play a positive effect in ignition kernel formation and combustion flame propagation. Yang et al. [22] experimental studied the effect of natural gas injection timing on the combustion performance and emissions in a diesel/natural gas dual-fuel engine. They compared the combustion performance and emissions under the varying natural injection timings under a single pilot fuel injection strategy. The result indicated that a certain degree stratification of natural gas distributions in-cylinder can be obtained by retarding the injection timing and the combustion process have been enhanced.

As can be seen from the above, the spray of pilot fuel and the natural gas distributions in-cylinder have a significant influence on the combustion performance and emissions in a diesel/natural gas dual-fuel engine. The split pilot fuel injection strategy and different natural gas supply method have been studied in order to explore the effects on the combustion process. However, the strategy of combining the split pilot fuel injection and varying natural gas injection timing is rarely studied this before and the combination strategy is believed one of the most promise ways to optimize the ignition kernels formation and flame propagation process in a diesel/natural gas dual-fuel engine [21,11]. So the effects of the combination strategy on the combustion performance and emissions characteristics should be intensively analyzed.

In this study, an experimental study was conducted to explore the effects of split pilot injection and natural gas injection timing on the combustion performance and emissions characteristics in a diesel/natural gas dual-fuel engine. Firstly, the effects of the varying natural gas injection timings under a fixed split pilot fuel injection operation condition were investigated. Then, a set of split pilot fuel injection timings was studied under an optimized natural gas injection timing operation condition. Moreover, the in-cylinder pressures, Heat Release Rate (HRR), PRR, ignition delay, flame development duration, CA50 and combustion duration, as well as regular emissions, have been also carefully analyzed in the paper. Additionally, the comprehensive analysis of combination split pilot fuel injection and natural gas supply method also provide a unique insight to fully understand how to optimize the dual-fuel combustion process and this is also the object of this investigation.

## 2. Experimental apparatus and procedure

### 2.1. Experiment engine and fuels

A diesel engine (G.W.2.8TC) produced by GREAT WALL Co. in China (four cylinders, water cooling, turbocharged, common-rail) have been modified to run in the diesel/natural gas dual-fuel combustion mode. More details of the experimental engine can be found in Table 1. Fig. 1 shows the schematic of the experimental setup. The engine equips an extra multi-point sequential port injection system to control natural gas in dual-fuel operation mode and four natural gas injectors are installed at intake manifold as close as possible to the intake valves for a better dynamic performance of natural gas supply. Compressed Natural Gas (CNG) with 25 MPa is stored in the CNG tank and its pressure is reduced to 0.4 MPa by a two-stage pressure regulator. And then through

**Table 1**
Specifications of the experimental engine.

| Item | Characteristics |
|---|---|
| Type | In-line four-cylinder common rail injection, turbocharged diesel engine |
| Combustion chamber | ω type |
| Bore × stroke | 93 mm × 102 mm |
| Compression ratio | 17.2:1 |
| Max. torque | 225 ± 5 N·m (1600–2600 $r{\cdot}min^{-1}$) |
| Injection system | Bosch CR1P2 |
| Max. injection pressure | 145Mpa |
| Diesel direct-injection nozzle | 6 × 0.137 mm |
| Natural gas injection nozzle | 1 × 3.0 mm |
| Valve timing | Opening Closing |
| Intake | 24°BTDC 55°ABDC |
| Exhaust | 54°BBDC 26°ATDC |

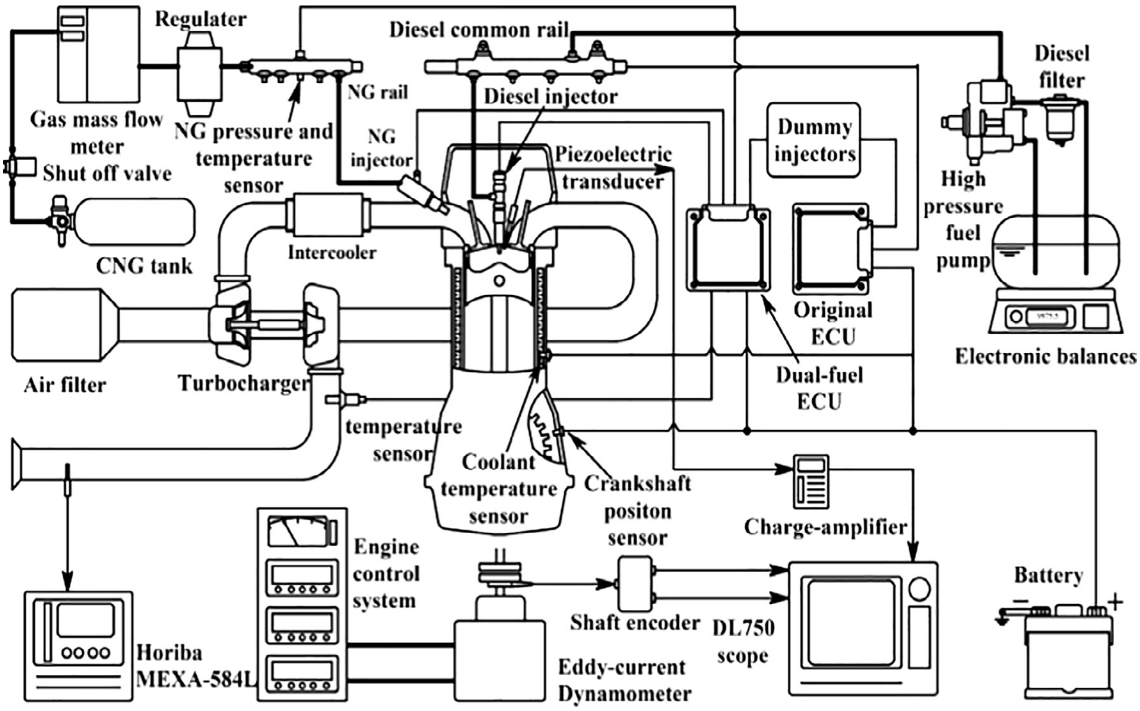


**Fig. 1.** The schematic of experimental setup.

a gas mass flow meter, natural gas is fed to the gas injectors. For the diesel supply, we just change the control unit and diesel supply is still depended on the original fuel system (Bosch CR1P2) in the experimental engine. An electrical control unit (ECU) developed by our team, referred as "dual-fuel ECU" in Fig. 1, is applied to independently manage the pilot fuel direct injection and natural gas multi-point sequential port injection events and the function of control diesel direct injection in original ECU is completely replaced by the dual-fuel ECU. Moreover, the dual-fuel ECU can provide the ability to vary the injection timing, injection duration as well as injection pressure according to the experimental requirements. More information about the dual-fuel ECU and the experimental engine can be found in Ref. [23]. Commercial natural gas and diesel were used in the dual-fuel combustion operation mode and the properties of the diesel and natural gas used in this experiment are given in Tables 2 and 3.

### 2.2. Instrumentations and data acquisitions

As shown in Fig. 1, a 100 kW eddy-current dynamometer was connected with the test engine in order to measure the engine load. An engine control system (Power-Link FC2000) was used for data acquisition. The coolant temperature, speed, torque, power as well as temperature and pressure of the lubricating oil were recorded during the experiment. Exhaust emissions were directly sampled from the exhaust pipe and an automotive exhaust emission analyzer (Horiba MEXA-584L) was applied to measure the regular exhaust emissions. A Kistler 6055C piezoelectric pressure transducer was installed in the cylinder head and the cylinder pressure was acquired by the transducer. Moreover, the original electric signal of the cylinder was amplified by a charge amplifier (Kistler 5011). The mass flow of diesel was measured by a high precise electric balance and natural gas consumption was obtained by a gas consumption meter (FC2212L). the measurement accuracy and other more details information about these instruments were provided in Table 4.

### 2.3. Experiment procedure and test operation conditions

The experiment was conducted at a constant speed of 1600 rpm and the load of the engine was around BMEP = 0.48 MPa. The inlet air temperature, coolant temperature, and lubricating oil temperature were kept constant at 20 ± 1 °C,80 ± 1 °C and 70 ± 1 °C, respectively. The valve timing diagram of the experimental engine is shown in Fig. 2. The varying of natural gas injection timing was experimental investigated under a split pilot fuel injection strategy. And then a group of split pilot injection strategies was tested and the first pilot injection timing was advanced from −11 °CA to −35 °CA. The split injection ratio is defined as the first pilot injection duration divided by the main injection duration and it fixed at 2/3 in the experiment. Test operating conditions are summarized in Table 5 and more details about experimental conditions can be found in the table.

## 3. Results and discussions

### 3.1. The effect of natural gas injection timings on the combustion performance and emissions characteristics under a split pilot injection strategy

The effects of natural gas injection timings on cylinder pressure and HRR under a split pilot injection condition were presented in Fig. 3. With retarded natural gas injection timings, the cylinder pressure increased significantly and the maximum value of the cylinder pressure was obtained under the latest natural gas injection case (−240 °CA).

**Table 2**
Properties of fuels used in this investigation.

| Fuel properties | Fuel type and value for following | |
|---|---|---|
| | Diesel | Natural gas |
| Low heating value, MJ/kg | 42.8 | 48.6 |
| Density, kg/m$^3$, ($T$ = 25 °C) | 834.8 | – |
| Viscosity, mm$^2$/s, ($T$ = 20 °C) | 3.393 | – |
| Cetane number | 52.5 | – |
| Octane number | – | 130 |
| Auto-ignition temperature, °C | 316 | 650 |
| Stoichiometric air-fuel ratio, kg/kg | 14.69 | 17.2 |
| Carbon content,% | 87 | 75 |

**Table 3**
Composition of natural gas.

| Component | Volumetric concentration (%) |
|---|---|
| Methane | 96.160 |
| Ethane | 1.096 |
| Butane | 0.136 |
| *Iso*-Butane, *n*-Butane | 0.021 |
| *Iso*-Pentane, *n*-Pentane | 0.006 |
| $N_2$ | 0.001 |
| $H_2S$ | 0.0002 |
| $H_2O$ | 0.006 |

**Table 4**
the characteristics of instrumentations.

| Variable measured | Device | Manufacturer and Model | Accuracy |
|---|---|---|---|
| Torque | Engine control system | Powerlink/GW160 | ± 0.2% FS |
| Speed | | Powerlink/FC2000 | ± 1 rpm |
| Temperature | Thermocouple | TC direct/K type | ± 2.5 °C |
| THC, CO and $NO_x$ | Automotive exhaust emission analyzer | Horiba MEXA-584L | THC: ± 12 ppm<br>CO: ± 0.06%<br>$NO_x$: ± 30 ppm |
| Diesel fuel mass flow | Electronic gravimetric balance | Beijing Heng Odd Instrument Ltd/HA-ES30K-1 | ± 0.1 g |
| Natural gas mass flow | Natural gas flow meter | Powerlink/FC2212L | ± 0.1 kg/h |

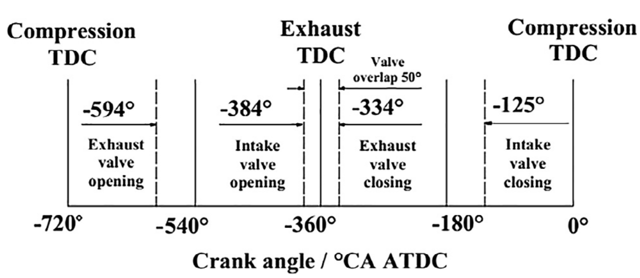


**Fig. 2.** Valve timing diagram.

The HRR curves shown the same tendency, and the maximum of the HRR increased from about 30 J/°CA under natural gas injection timing −500°CA case to almost 75 J/°CA under the −240°CA case. This result is in accord with that we reported previously [22] and mainly due to retarding natural gas injection timing produced some kind of stratification natural gas-air mixture before pilot injection and natural gas combustion rate was enhanced. The results indicated that natural gas stratification is still played the important roles under the split pilot injection strategy and certain stratification of natural gas is capable to enhance the ignition kernel formation and flame propagation inside the chamber, especially under a low load operating condition. However, there was an interesting difference from previous studies [12,19]. Under the single pilot injection conditions, it is well known that the first peak of HRR usually represents the combustion of the pilot diesel and the maximum value indicated the mass of pilot diesel that participated

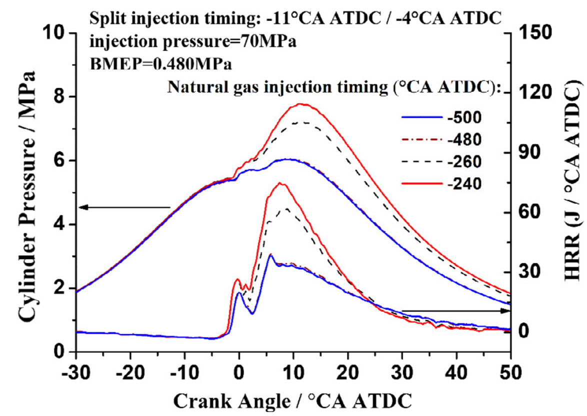


**Fig. 3.** Cylinder pressure and HRR versus natural gas injection timings under split pilot injection strategy.

in this process [24]. And the second peak of HRR produced by the premixed combustion of natural gas. Moreover, in most cases, the second peak of HRR is lower than the first peak of HRR because the diesel combustion speed is faster than that of natural gas [25]. However, under split injection strategy, the first peak of HRR is significantly reduced while the second peak of HRR is dramatically enhanced. This is due to the fact that less diesel (mainly is the first pilot injected diesel) burned in the first stage of the HRR curve and the mixture of the main injected diesel and natural gas was ignited simultaneously by the first pilot injected diesel. So the second peak of HRR was enhanced significantly.

Fig. 4 depicts the PRR under different natural gas injection timings and it can be used as an index of combustion noise performance. With retarded natural gas injection timings, the maximum of PRR is increased and the value of the PRR is obviously higher in later injection timings condition (−260 °CA and −240 °CA) compared with that in earlier cases (−500 °CA and −480 °CA). In addition, the second peak of the PRR is very sensitive to the variation of natural gas injection timing and the value increase from about 0.15 MPa/°CA to around 0.37 MPa/°CA and the combustion noise is slightly enhanced. This result indicated that the first stage combustion (the first pilot injected diesel) is weakened and the second combustion stage (natural gas premixed combustion) is enhanced. So the maximum combustion noise is reduced compared with that under a single pilot injection strategy.

The CA50 and combustion duration are very important parameters to evaluate the combustion development process. The variation of CA50 and the combustion duration with varying natural gas injection timings under split pilot injection strategy are provided in Fig. 5. With retarded natural gas injection timings, the CA50 shift to the TDC while the value changed slightly (from about 10 °CA ATDC to around 8.75 °CA ATDC). The combustion duration is reduced with retarding natural gas injection timing and the maximum reduction is up to 30%. The experiment results indicated that the combustion process was accelerated by retarding natural gas injection timing. And this is the evidence that the stratification produced by retarding natural gas injection timing have a positive effect on the premixed combustion of natural gas and it is in accord with that we observed in Fig. 3.

**Table 5**
Test operation conditions.

| NO | Engine speed (r/min) × natural gas injection pressure (MPa) × BMEP (MPa)[a] | CNG/pilot fuel flow rate/(kg/h) | Pilot injection pressure/MPa | First pilot injection timing/°CA ATDC | Main injection timing/°CA ATDC | Natural gas injection timing/°CA ATDC |
|---|---|---|---|---|---|---|
| 1 | 1600 × 0.4 × 0.48 | 4.064/0.724 | 70 | −11 | −4 | −500/−480/−260/−240 |
| 2 | | | 70 | −11/−14/−17/−20/−25/−30/−35 | −4 | −240 |

[a] BMEP values are calculated under natural gas injection timing of −500 CA ATDC.

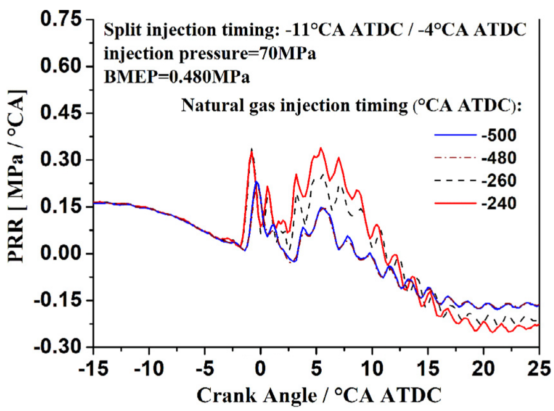


**Fig. 4.** PRR versus natural gas injection timings under split injection strategy.

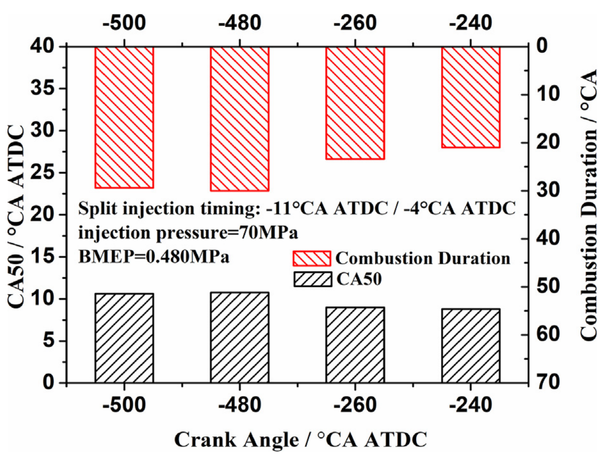


**Fig. 5.** The CA50 and combustion duration versus different natural gas injection timings.

As we all know, the THC, CO, and $NO_x$ are the mainly regular emissions in a diesel/natural gas dual-fuel engine. Moreover, it had been confirmed that over 90% of THC emissions in a diesel/natural gas dual-fuel engine are unburned methane [26] and improving the natural gas combustion efficiency will reduce the THC emissions. Under the specific air/fuel ratio, the CO emissions are significantly dependent on the in-cylinder temperature, which governs the charger's oxidation and decomposition. $NO_x$ emissions are commonly believed that the maximum temperature of combustion is directly relative with the production of $NO_x$. The THC, CO and $NO_x$ emissions with varying natural gas injection timings under split pilot fuel injection strategy are provided in Fig. 6, respectively. The THC decreased with retarding natural gas injection timings and the CO shows the same tendency with the variation of natural gas injection timings. This is probably due to the facts that retarded natural gas injection timing provided a stratification-like mixture. Therefore, the premixed combustion of natural gas was accelerated as shown in Fig. 3 and unburned methane was reduced. Especially under a split pilot injection strategy, the main injected diesel involved in the premixed combustion of natural gas. As a result, the combustion flame propagation process was accelerated and natural gas combustion efficiency was improved. Consequently, the average in-cylinder temperature was increased and CO emissions are inhibited. Moreover, the combustion process was accelerated by retarding natural gas injection timings and the combustion duration was reduced. So the maximum temperature of combustion increased and then the $NO_x$ emissions were promoted.

### 3.2. The effect of split injection timings on the combustion performance and emissions

The pilot injection timing is a very important parameter in a dual-fuel combustion engine and the split pilot fuel injection is an effective method to improve the ignition kernel formation process and its spatial distribution in-cylinder. The cylinder pressure and HRR curves with the variation of first pilot injection timings are shown in Fig. 7. We can find that keeping the main injection timing fixed at −4 °CA ATDC and just advancing the first pilot injection timings from −11°CA ATDC to −25°CA ATDC, maximum cylinder pressure in those curves increased obviously and the crank angle corresponding to the maximum cylinder pressure shifted to the TDC. But further advanced the first pilot injection timings to −35°CA ATDC, the phase of HRR was retarded. Moreover, observing the HRR curves, we can find that the peak of HRR increased with advanced the first pilot injection timing from −11°CA ATDC to −25°CA ATDC and the crank angle responding to the peak value of HRR is also advanced. But advanced first pilot injection timing from −25°CA ATDC to −35°CA ATDC, the HRR changed from a bimodal curve to a single one and the crank angle responding to the peak value of the curve is retarded. The results indicated that the first peak of the cylinder pressure curve is depended on the first pilot diesel injection timing and further advanced the first diesel injection timing, the pilot diesel have enough time to form a homogenous mixture with natural gas and air. As a result, the start of combustion was retarded and the first pilot injected diesel almost start combustion as the same time with the main injection. So we can clearly observe that the HRR curve exhibited a single peak when further advanced first pilot injection timing to −35°CA ATDC. Moreover, the first pilot injection timing has a significant influence on the combustion performance of the main injected diesel. In an appropriate range, such as from −11°CA ATDC to −25°CA ATDC, the combustion of the first pilot injected diesel produced high-temperature region and the ignition and flame propagation of the main injected diesel are significantly enhanced by the high-temperature region. However, further advanced first pilot injection timing to −35°CA ATDC, the influence between the first pilot injection and the main injection was weakened due to the main injected diesel spray far away from the high region formed by the combustion of the first pilot injected diesel [19].

The variation of the PRR under different split pilot fuel injection strategy is shown in Fig. 8. According to the Figure, we can find that with retarded first pilot diesel injection timings from −11°CA ATDC to −25°CA ATDC, the maximum value of the PRR was increased and the crank angle responding to the peak of the PRR advanced. But further advanced the first pilot injection timing to −35°CA ATDC, the maximum value of the PRR decreased and the crank angle responding to the

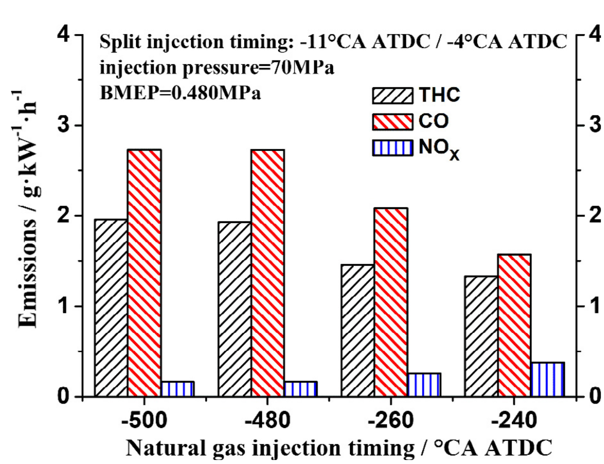


**Fig. 6.** HC, CO and $NO_x$ emissions versus natural gas injection timing under split pilot injection strategy.

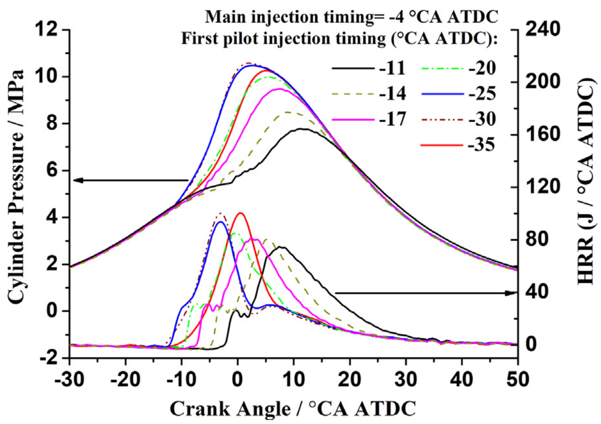


**Fig. 7.** The cylinder pressure and HRR under different split pilot fuel injection strategies.

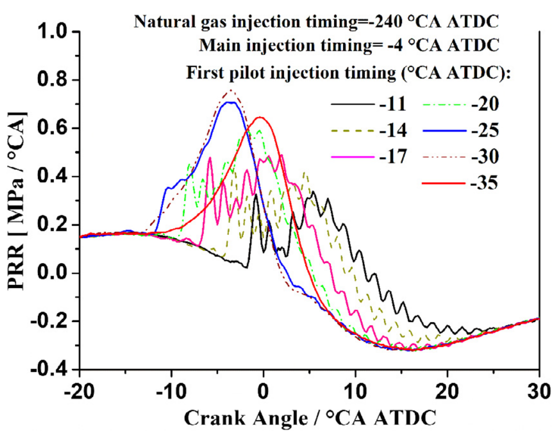


**Fig. 8.** PRR under different split pilot injection strategy.

peak of the PRR retarded. Moreover, the shape of the PRR changed from a bimodal curve to a single one and this result is in accord with the previous cylinder pressure and HRR. Moreover, this result indicated that the split pilot injection strategy has a significant influence on the combustion process of dual-fuel.

As far as the ignition delay and flame development duration are concerned in Fig. 9, the ignition delay obviously increased with advancing the first pilot injection timings from −11°CA to −35°CA. The flame development duration is reduced with advancing the first pilot injection timings from −11°CA to −20°CA and then it significantly increased with advancing the first pilot injection timings from −25°CA to −30°CA. Additionally, further advancing the first pilot injection timing to −35°CA, the flame development duration is not significant variation. The results indicated that advancing the first injection timing, the pilot diesel and natural gas-air mixture have more time to mix and the more homogenous charger was formed in the cylinder. So the ignition delay was prolonged with advancing the first pilot injection timing. On the other hand, varying the first pilot injection timing from −11°CA to −20°CA, more natural gas entrained into the spray of the first pilot injected diesel and the combustion of the first pilot injected diesel produced the high-temperature region in the cylinder and the combustion of main injected diesel was enhanced. So the flame development process was accelerated. But further advanced the first pilot injection timings, the high-temperature region formed by the combustion of the first pilot injected diesel far away from the main injection diesel spray gradually and the influence on the main injected diesel is weakened. So the flame development duration is prolonged. In the same reason, when the dwell time between first pilot injection and the main injection is long enough, the flame development process is almost not influenced by the first pilot injection timings. So further advanced first pilot injection timings to −35°CA, the flame development duration didn't change significantly. We can find more evidence in the CA50 and combustion duration curves in Fig. 10.

The CA50 and combustion duration under varying first pilot injection timings are shown in Fig. 10. Observing the curves, we can find that the CA50 shifts to the TDC with advancing the first pilot injection timing from −11°CA to −25°CA and then, further advanced the first pilot injection timing to −35°CA, the CA50 moves away from the TDC. This result clearly illustrated that the CA50 is dependent on the first pilot injection timings. The curve of the combustion duration exhibits an obvious reverse tendency compared with the CA50 and the longest combustion duration obtained under the −25°CA. Moreover, varying the first pilot injection timings from −11°CA to −25°CA, the combustion duration prolonged. The result indicated that the flame propagation speed is influenced by the dwell time between the first pilot injection and the main injection. With advanced first pilot injection timings, the dwell time increased and the high-temperature region formed by the combustion of the first pilot injected diesel is far away from the main injection diesel spray. So the effect of the high-temperature region on the main injected diesel spray is gradually weakened and the flame propagation speed is gradually slower, particularly in the later of the combustion process. And then, further advanced first pilot injection timings, the combustion mode changed and the most diesel injected by the first pilot participated in premixed combustion. Sequentially, the combustion duration is reduced. And this result agrees well with the HRR curves shown in Fig. 7.

The regular emissions (THC, CO, and $NO_x$) under varying first pilot injection timings are shown in Fig. 11. The THC and CO emissions in a diesel dual-fuel engine are mainly due to an over lean charge and the incomplete combustion of fuels in the cylinder. We can find that the THC emissions are not sensitive to the variation of the first pilot injection timings and the maximum of the THC emissions is no more than 1.75 $g \cdot kW^{-1} \cdot h^{-1}$. The CO emissions exhibit not obvious tendency over the variation of the first pilot injection timings. $NO_x$ emissions are believed to relative to the maximum combustion temperature and oxygen concentration in-cylinder. A higher combustion temperature and richer oxygen, as well as a longer combustion duration in the cylinder, will result in more $NO_x$ formation. As Fig. 11 depicts, with advanced first pilot injection timings, the $NO_x$ emissions first increased and then decreased. When further advanced first pilot injection timings from −25°CA to −30°CA, the maximum of $NO_x$ emissions are obtained at −25°CA and respond to the longest combustion duration in Fig. 10.

## 4. Conclusions

In this paper, the effects of natural gas injection timings under a

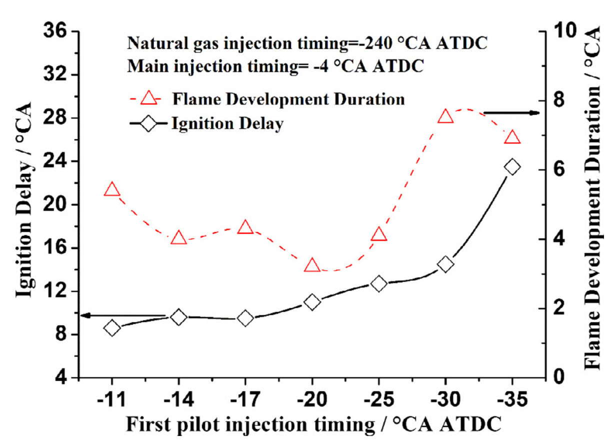


**Fig. 9.** Ignition delay and flame development duration under different first pilot injection timings.

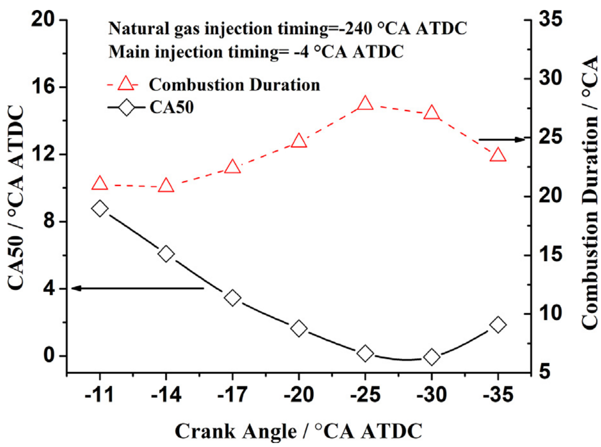


**Fig. 10.** CA50 and combustion duration under different first pilot injection timings.

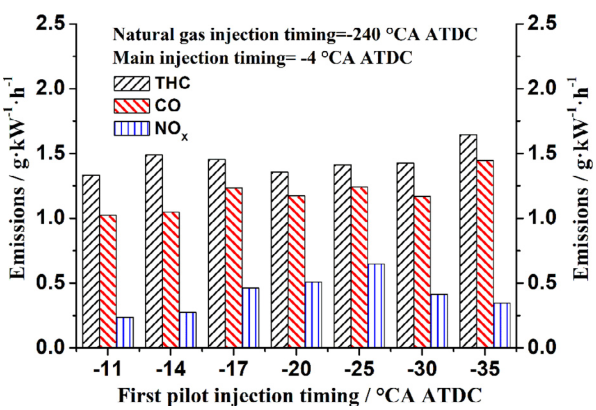


**Fig. 11.** THC, CO and $NO_x$ emissions versus different first pilot injection timings under split injection strategy.

split pilot injection operation condition and the first pilot injection timings on the combustion performance and emissions characteristics of a diesel/natural gas dual-fuel engine were experimentally investigated. The cylinder pressure, HRR and regular emissions have been measured. The PRR, ignition delay, flame development duration, CA50 as well as combustion duration were calculated for analyzing. On the basis of the experiment results and analyses, the main conclusions of the investigation are summarized as follows:

(1) Under a split pilot injection operation condition in a diesel/natural gas dual-fuel engine, the first stage (pilot diesel premixed combustion) of the combustion is weakened while the second combustion stage (natural gas premixed combustion) is enhanced compared with that under a single pilot injection strategy. The combustion duration and noise are also reduced under the split pilot injection strategy. In addition, with retarding natural gas injection timings under the split pilot injection operation conditions, natural gas premixed combustion stage accelerated significantly, the maximum value of HRR is obtained at the latest natural gas injection timing of −240°CA ATDC and it is almost two times compared with that at the earlies case of −500°CA ATDC. The combustion duration reduced about 30% with retarding the natural gas injection timings from −500°CA to −240°CA ATDC. Moreover, the THC and CO emissions are reduced while the $NO_x$ emissions are promoted by retarding natural gas injection timings.

(2) In a split pilot injection strategy, the combustion performance is significantly dependent on the dwell time between the first pilot injection and main injection. The influence of interaction between the combustion of the first pilot injected diesel and the main injected diesel is gradually reduced with increased the dwell time by advancing the first pilot injection timing. Particularly, at the first pilot injection timing of −25°CA ATDC, the HRR start to change from a bimodal curve to a single one. Moreover, from the view of improving combustion performance, the range of optimal dwell time is from 20°CA to 30°CA in this study.

(3) The natural gas injection timings and the split pilot injection strategy are very important factors to influence the combustion performance and emissions characteristics in the diesel/natural gas dual-fuel engine. Combination the reasonably retarded natural gas injection timing and keep a certain dwell time between the first pilot injection and the main injection is an effective way to optimize the combustion performance and emissions characteristics in a diesel/natural gas dual-fuel engine.

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