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Parametric investigation of natural gas port injection and diesel pilot injection on the combustion and emissions of a turbocharged common rail dual-fuel engine at low load

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HIGHLIGHTS

- Effects of CNG injection timing studied under different pilot injection timings.
- Effects of CNG injection timing studied under different pilot injection pressures.
- Delayed CNG injection timing improves engine performance at low load in most cases.
- Higher pilot injection pressure obtains better BTE and emissions except for NO_x.
- Advanced pilot injection timing obtains better BTE and emissions except for NO_x.

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ABSTRACT

In this paper, a common rail diesel research engine was converted to operate in dual-fuel mode and extensive experiments were conducted to investigate the effects of natural gas injection timing on the combustion and emissions performance under different pilot injection pressure and timing at low load conditions. The presented results include the cylinder pressure, heat release rate (HRR), ignition delay, combustion duration and brake thermal efficiency, as well as CO, HC and NO_x emissions at different natural gas injection timing under pilot injection pressure (46 and 72 MPa) and pilot injection timing ($-8°$ and $-17°$ ATDC) operation conditions at low load (BMEP = 0.24 MPa). The results indicated that retarded natural gas injection timing can achieve a stratified-like air–fuel mixture in cylinder under the different pilot injection conditions, which provided a method to improve the combustion performance and exhaust emissions at low load. Moreover, under higher pilot injection pressure (72 MPa) conditions, better combustion performance, such as shorter ignition delay and combustion duration, higher brake thermal efficiency, were achieved; however, the exhaust emissions significantly increased compared with those under lower pilot injection pressure (46 MPa). On the other hand, under the advanced pilot injection timing ($-17°$ ATDC), the combustion performance was radically better, THC and CO emissions were lower but the NO_x emissions were significantly higher compared with those under the regular pilot injection timing ($-8°$ ATDC). This is attributed to faster flame propagation speed, better combustion phasing and higher volumetric efficiency. Consequently, employing appropriate natural gas injection timing accompanied with reasonable pilot injection parameters is critical to further improve combustion performance and exhaust emissions of a dual-fuel engine at low loads.

1. Introduction

In order to meet stringent emission regulations, a lot of technical approaches have been proposed in recent years [1–4]. And from the view of improving the economy of the diesel engines and reducing air pollution, the dual-fuel concept has been widely employed in existing diesel engines. And in the typical dual-fuel engine, the gas as the primary fuel is 'sparked' by a very small amount of auto-ignited pilot diesel, which is directly injected into cylinder near the top dead center (TDC) using the original diesel fuel injection system. Additionally, these dual-fuel engines still maintain full diesel capability in case gaseous fuel is not available. It has the combined benefits in reducing the harmful exhaust

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emissions (significantly lower NO_x and PM) and operation cost compared to the conventional diesel engines, as well as more freedom in the fuel supply. In addition to natural gas, various gaseous fuels such as biogas, synthesis gas and hydrogen [5–9] have been used in the dual-fuel engine. Natural gas is world widely used and has attractive price and lower exhaust emissions. Moreover, due to its high octane number, it is more suitable for C.I. engines which usually operate with relatively high compression ratio. Therefore, natural gas seems to be the most promising gaseous fuels for IC engines, and natural gas/diesel dual-fuel combustion concept has received considerable attention from researchers and engine manufactures [10–12].

In recent years, various investigations have previously been conducted to explore the parametric effects on the combustion and emissions performance of dual-fuel engines [10,13–20]. And the dual-fuel combustion has been proved to be one of the most practical ways to improve the economy and reduce the harmful emissions of the conventional diesel engines in those studies. However, there are still some critical problems in the dual-fuel operation mode and many investigations have also confirmed that at low load, natural gas dual-fuel engine inevitably suffers from unstable combustion performance and higher emissions of CO and unburned CH_4. Moreover, it is well known that those problems mainly due to over-lean natural gas–air mixture in cylinder at low load [10]. To overcome those obstacles, Srinivasan et al. [21] analyzed the effects of intake charge temperature and pilot quantity at low load in a dual-fuel engine, and they reported that increasing intake charge temperature was an effective strategy to improve the combustion performance, stability and emissions at low load; Su et al. [22] investigated the effects of the partial gas cut-off, intake air throttling and increasing pilot fuel quantity on emissions and the brake thermal efficiency of the NG/diesel dual-fuel engine, and both advantages and disadvantages of those technical approaches were discussed. Zhou et al. [23] studied the influences of hot EGR on combustion performance and emissions characteristics at part loads in a dual-fuel engine and reported that the hot EGR had the merits to fulfill lower emissions and improve the engine performance. Generally speaking, technical methods mentioned above could improve the performance of the dual-fuel engine at low load. But those methods depend on extra equipments and thus increase the operation cost and the complexity of the engines. However, the combustion of the dual-fuel engine is strongly influenced by the way of natural gas–air–diesel mixture in cylinder [24]. And in natural gas port injection dual-fuel engines, the stratification mixture, which can be obtained by varying natural gas injection timing, has obviously positive effects on accelerating the combustion process of dual-fuel engine, especially at low load. And unfortunately, the effects of natural gas injection timing variation on the combustion and emissions in the dual-fuel engine at low load are not carefully evaluated. Moreover, there is little information about how to optimize the combustion performance and emissions characteristics at low load through combinations of the diesel pilot injection parameters (timing and pressure) and natural gas injection timing, which is the objective of this work.

2. Experimental apparatus and procedure

2.1. Test engine

The experiment engine was converted from a four-cylinder, water cooling, direct injection, turbo-charged, common rail diesel engine which was manufactured by GREAT WALL in China. The specifications of the engine are listed in Table 1.

The original diesel engine requires a few modifications on the injection system to be compatible with dual-fuel combustion, and the natural gas injection system was installed at the intake manifold in order to control natural gas supply. As shown in Fig. 1, the original electronic control unit (ECU) is retained and a dual-fuel ECU, especially developed for this work [25], is added to cooperate with the original ECU. The crank shaft angle, cam and common rail pressure signals are shared by both ECUs. Under dual-fuel operation conditions, both the diesel and natural gas injectors are completely controlled by the dual-fuel ECU and the original diesel injection command is by-passed as dummy load from the original diesel system, but instead it is used by the dual-fuel ECU to compute the amount of both the diesel and CNG injection. Other than this, the original ECU performs exactly the same way in a normal diesel engine.

Table 1
Specifications of the test 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	
Injection system	Common rail	
Max. injection pressure	145 MPa	
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

2.2. Fuel and fuel supply system

In this study, diesel was used as the pilot fuel and natural gas was employed as the main fuel. The commercial diesel fuel and natural gas were used in the experiment and the properties of the fuels are given in Tables 2 and 3.

As shown in Fig. 1 the natural gas supply system consisted of a high pressure natural gas tank, a two-stage pressure regulator and a shut off solenoid valve as well as natural gas injectors. When natural gas flows through the regulator, the pressure of natural gas is decreased from about 25 MPa to 0.4 MPa. After that, natural gas is sequentially injected into the intake manifold by natural gas injectors. Both the quantity and the timing of natural gas are controlled by the dual-fuel ECU.

2.3. Instrument arrangement and data acquisition

The engine loads and speeds were controlled manually by a 100 kW eddy-current dynamometer. The torque, exhaust gas and coolant temperature as well as lubricating oil pressure and temperature were monitored by the Power-Link engine control system (Model FC2000). The pilot diesel consumption rate was measured by a high precision electronic balance with the accuracy of ±0.1 g and natural gas was measured using a FC2212L gas consumption meter with the accuracy of ±0.01 kg/h. Exhaust emissions were sampled directly from the exhaust pipe. Total unburned hydrocarbon (THC), carbon monoxide (CO), carbon dioxide (CO2) and nitric oxides (NO_x) emissions were measured by a Horiba MEXA-584L automotive exhaust emission analyzer with accuracies of ±12 ppm, ±0.06%, 0.5% and ±30 ppm respectively, while PM (Particulate Matter) emissions was measured by a Horiba MEXA-600S opacimeter with a display resolution of ±0.001 m^{-1}. The cylinder pressure was measured by a Kistler 6055C piezoelectric pressure transducer in conjunction with a Kistler 5011 charge amplifier. All data were saved to Yokogawa DL750 which recorded

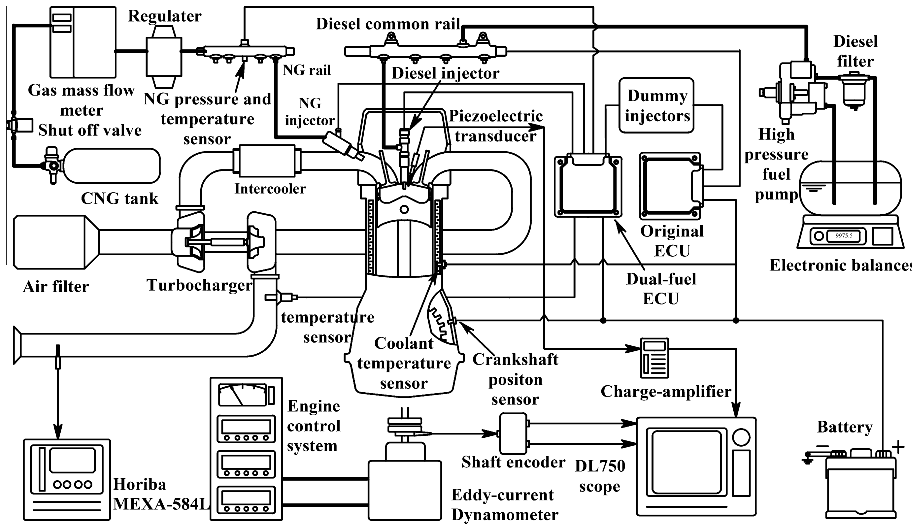

Fig. 1. Engine set-up and instrumentation layout.

Table 2
Test fuel properties.

Fuel properties	Diesel	Natural gas
Low heating value (MJ/kg)	42.8	48.6
Cetane number	52.5	–
Octane number	–	130
Auto-ignition temperature (°C)	316	650
Stoichiometric air–fuel ratio	14.69	17.2
Carbon content (%)	87	75

Table 3
Natural gas composition.

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

200 continuous cycles with a resolution of 0.2° crank angle (CA) for combustion performance analysis.

2.4. Experiment procedure and test conditions

The air inlet temperature is fixed at 20 °C for all test conditions. The coolant temperature is kept around 75 °C and the lubricating oil temperature is kept about 65 °C during the experimental process. All experiments are carried out at a constant speed of 1600 rpm and engine load corresponding to break mean effective pressure (BMEP) of 0.24 MPa, at two different pilot injection pressures and timings but under the various natural gas injection timing. In addition, the pilot fuel and natural gas quantity (N.G. injection duration) are constant all over the experiment and the operation conditions are summarized in Table 4. And those experiments, which are carried out at natural gas injection timing −480° ATDC in each set, are used to simulate the conventional dual-fuel engines with a mixer and the results of those cases are used as baseline in this study. Natural gas injection timing is defined as the crank angle at which the solenoid of natural gas injector was energized in this paper. The percent energy substitution rate is calculated as following:

$$\mathrm{PES} = \frac{\dot{m}_{NG} LHV_{NG}}{\dot{m}_D LHV_D + \dot{m}_{NG} LHV_{NG}} \times 100\% \qquad (1)$$

3. Results and discussions

Before we discuss the results, the ignition delay and combustion duration should be defined: the ignition delay is the interval crank angles between pilot injection and ignition. In this paper, ignition is identified by the crank angle at which 10% mass (pilot diesel and natural gas) fraction is burned; the combustion duration is the period in crank angles from 10% to 90% mass fraction burn, or CA_{10-90}.

3.1. The effects of natural gas injection timing and pilot injection pressure on combustion performance

The pilot injection pressure and timing have dramatic effects on the pilot spray formation which should be included for investigation when studying the effects of natural gas injection timing. To simplify the discussion, we limit the first part of the CNG injection timing results to the more regular pilot injection timing at −8° ATDC (case 1 and 2 in Table 4) , before we investigate the effects of pilot injection timing later in this paper (case 3 in Table 4).

Fig. 2 shows the heat release rate (HRR) and cylinder pressure traces under the different natural gas injection timings operation for pilot injection pressures of 46 and 72 MPa. A typical combustion process of dual-fuel engine can be identified to take place in three stages: the first stage is premixed combustion of pilot diesel and a small part of entrained gaseous fuel; the second stage is the premixed combustion of gaseous fuel where the majority of the gaseous fuel is burned; the third stage, which is diminishing and less well-defined, is the diffusion combustion of residual pilot diesel fuel and gaseous fuel [10,26,27].

Referring the Fig. 2, the cylinder pressure and the second peak (corresponding to the premixed combustion of natural gas) of HRR curves increased with the retarded natural gas injection timing. This is due to the fact that retarded natural gas injection timing facilitated a stratified-like air–fuel mixture in the cylinder [24]. The resultant mixture stratification reduced the local over-lean areas and enhanced the flame propagation of natural gas initial

Table 4
Experimental cases.

No.	Engine speed (r/min) × natural gas injection pressure (MPa) × BMEP (MPa)[a]	Pilot injection pressure/MPa	Pilot injection timing/°CA ATDC	λ	PES/%
1	1600 × 0.4 × 0.24	46	−8	2.067	85
2		72	−8		
3	1600 × 0.4 × 0.33	72	−17		

[a] BMEP calculated under natural gas injection timing of −480° after top dead center (ATDC).

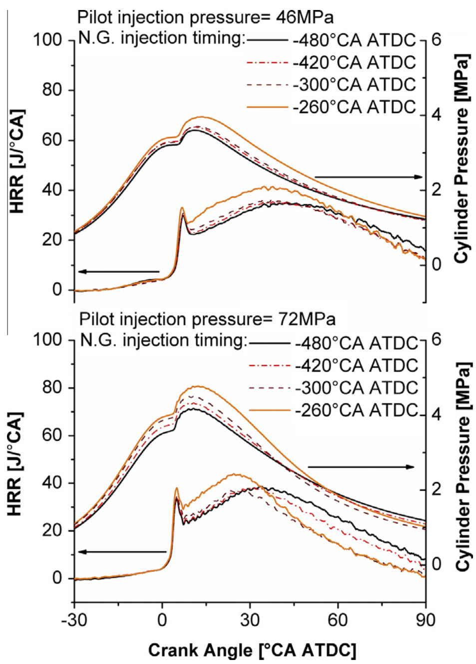

Fig. 2. HRR and cylinder pressure traces under different natural gas injection timing operation for 46 and 72 MPa of pilot injection pressure at pilot injection timing = −8° ATDC.

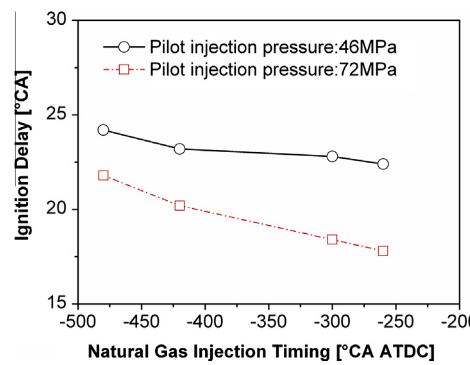

Fig. 3. The ignition delay under different natural gas injection timing operation for 46 and 72 MPa pilot injection pressure at pilot injection timing = −8° ATDC.

combustion and stabilized the residual lean burn-out phase. Comparing the curves for the different pilot injection pressure cases in the Fig. 2, we can find that the cylinder pressure and the peak value of HRR under the condition of pilot pressure 72 MPa are higher than those of 46 MPa. This is mainly due to longer spray penetration distance and more entrained natural gas inside the pilot spray when the pilot pressure is higher. As a result, the number and the distribution range of ignition centers under the high pilot injection pressure are much more than those under lower pilot pressure conditions, which obviously have a positive effect on the dual-fuel combustion. Furthermore, it seems that the effects of natural gas injection timing on combustion performance are not significantly different under the two pilot injection pressures, which suggests that retarded natural gas injection timing just formed a stratified-like air–fuel mixture in cylinder and probably did not affect the pilot spray. The natural gas injection timing also affects the cylinder compression pressure in a complex way primarily due to the interactions of volumetric efficiency, combustion phasing of this engine, and specific heat ratio effects. In general the compression pressure is higher with the retard of natural gas injection timing, due to faster combustion.

The variations of ignition delay under the 46 and 72 MPa pilot injection pressure operation as a function of natural gas injection timing at pilot injection timing = −8° ATDC is given in Fig. 3. The ignition delay is significantly decreased with retarded natural gas injection timing under either pilot injection pressure 46 MPa or 72 MPa. And it is indicated that the retarded natural gas injection timing probably produced a stratified-like air–fuel mixture and reduced local over-lean areas in cylinder. As a result, the flame propagation of natural gas combustion is enhanced. The ignition delay under the higher pilot injection pressure of 72 MPa in Fig. 3 is significantly shorter than that of 46 MPa cases, proving the previous hypothesis that higher pilot injection pressure leads to more ignition sources and more entrained natural gas inside the pilot spray. Consequently, the process of flame kernel formation and development are accelerated. Similar conclusions can be drawn from the combustion duration or CA_{10-90} shown in Fig. 4.

The variations of brake thermal efficiency (BTE) under the pilot injection pressure 72 and 46 MPa as the function of natural gas injection timing are given in Fig. 5. The higher pilot injection pressure cases at 72 MPa yield consistently higher BTE than those under the lower 46 MPa. The highest BTE is observed at the latest natural gas injection timing under both pilot injection pressures. Moreover, the former and its result are consistent with the observation that the retarded natural gas injection timing enhanced the ignition kernel initialization and flame propagation of the dual-fuel combustion and also has better combustion phasing to achieve the best BTE.

3.2. The effects of natural gas injection timing and pilot injection pressure on exhaust emissions

Fig. 6 shows the variation of BSTHC, $BSNO_x$ and BSCO respectively, versus different natural gas injection timing at 1600 rpm and pilot injection timing = −8° ATDC, for both pilot injection pressures. Both the BSTHC and BSCO under the higher pilot injection pressure 72 MPa are slightly higher compared with those under the lower injection pressure of 46 MPa. Moreover, the lowest BSTHC and BSCO emissions are achieved at the most retarded natural gas injection timing tested. The higher pilot injection pressure may lead to more spray impingement on the piston and cylinder wall. As a result, the BSTHC and BSCO are higher under the high pilot injection pressure (72 MPa) compared with those under the low pilot injection pressure (46 MPa) operation conditions. And the effects of natural gas injection timing on the emissions of BSTHC and BSCO are not obviously discrepant under the different pilot injection pressures, indicating that the pilot diesel spray is not strongly affected by the variation of natural gas injection

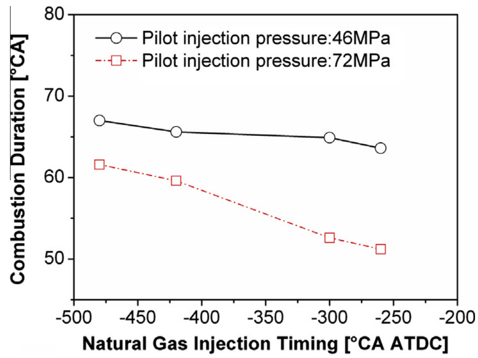

Fig. 4. The combustion duration under different natural gas injection timing operation for 46 and 72 MPa pilot injection pressure at pilot injection timing = −8° ATDC.

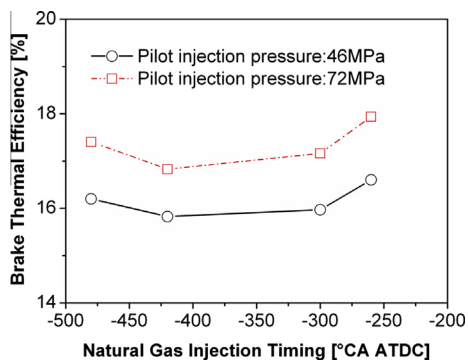

Fig. 5. The BTE under different natural gas injection timing operation for 46 and 72 MPa pilot injection pressure at pilot injection timing = −8° ATDC.

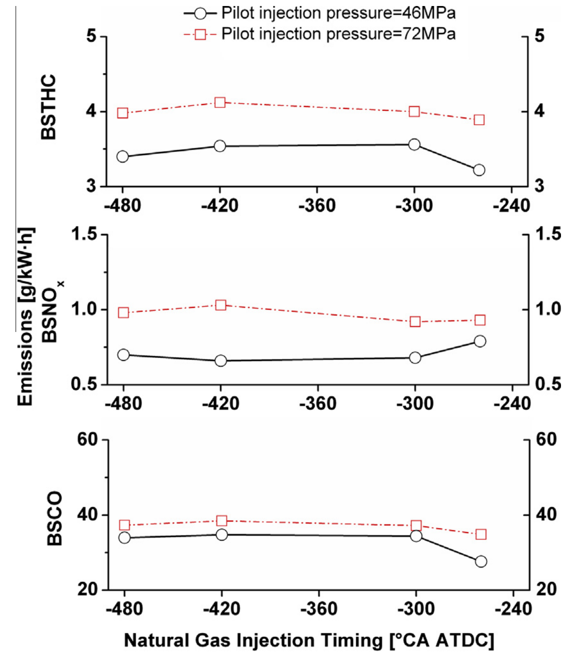

Fig. 6. The BSTHC, $BSNO_x$ and BSCO under different natural gas injection timing operation for 46 and 72 MPa pilot injection pressure at pilot injection timing = −8° ATDC.

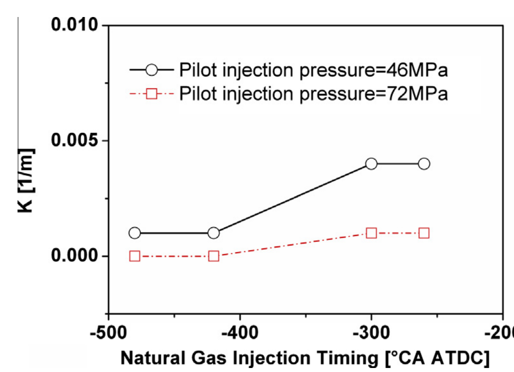

Fig. 7. The PM emissions (expressed in light absorption coefficient or *K* value) under different natural gas injection timing operation for 46 and 72 MPa pilot injection pressure at pilot injection timing = −8° ATDC.

timing. Additionally, it is obvious that the higher $BSNO_x$ under 72 MPa pilot injection pressure is consistent with most diesel combustion literatures [19,28], and is primarily due to the higher premixed combustion fraction which occurs at higher temperature.

The PM emissions under different natural gas injection timing operation for 46 and 72 MPa pilot injection pressure at pilot injection timing = −8° ATDC are provided in Fig. 7. And the PM emissions under dual-fuel operation mode are extremely low due to the methane (CH_4), which is the primary constituent of natural gas, has no carbon–carbon bonds with high hydrogen to carbon ratio, and thus, leading to lower tendency to produce particulate matter [16]. Moreover, the PM emissions under 46 MPa operation conditions are consistently higher compared with that under 72 MPa cases and with retarded natural gas injection timing, the PM emissions slightly increased under the 46 MPa and 72 MPa operation conditions. Higher pilot injection pressure means longer spray penetration distance and more entrained natural gas inside the pilot spray. Therefore, under 72 MPa operation conditions, the over-rich and high temperature region of the pilot fuel spray is inhibited and most pilot diesel burned in the premixed combustion process, which result in an obviously decrease of PM emissions. On the contrary, the stratified mixture, which is obtained with retarded natural gas injection timing, leads to the local over-rich region and increase PM emissions.

3.3. The effects of natural gas injection timing and pilot injection timing on combustion performance

The pilot injection timing has significant effect on the ignition sources formation and distribution. Therefore, the effect of natural gas injection timing under different pilot injection timings should be further studied in order to optimize the combustion process and exhaust emissions of dual-fuel engine at light loads. Fig. 8 shows the cylinder pressure and heat release rate curves of the two diesel pilot injection timing, both of which have the similar and typical three-stage dual-fuel combustion discussed earlier. For the two pilot injection timing cases investigated, the cylinder pressure and HRR curves both increased with the retarded natural gas injection timing. This is due to that retarding natural gas injection timing provided a better stratified air–fuel mixture in the cylinder, consisting with the first part of results discussed earlier. Fig. 8 also shows that under earlier pilot injection timing at −17° ATDC, both the cylinder pressure and HRR are much higher compared with the more conventional −8° ATDC pilot injection timing conditions, because advancing pilot injection timing leads to faster and much better combustion phasing, as a result of the earlier heat release and the higher peak pressure closer to TDC.

The ignition delay curves versus natural gas injection timing operation for the two pilot injection timings are given in Fig. 9. The ignition delay of the advanced pilot injection (−17° ATDC) is

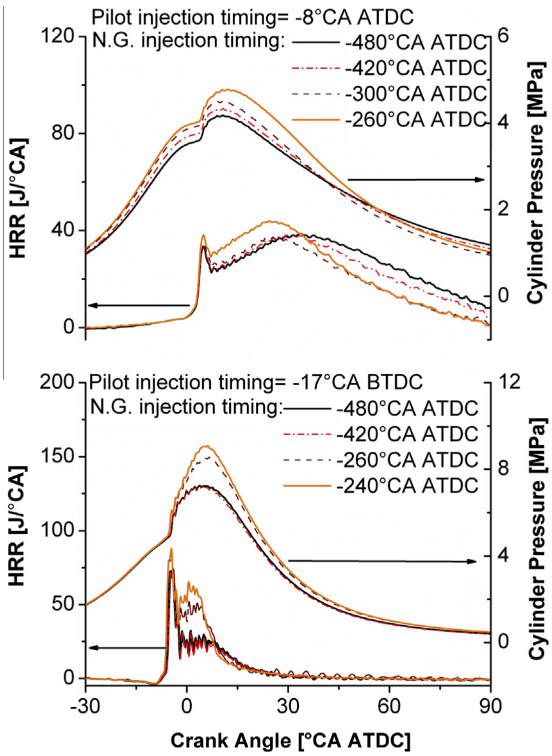

Fig. 8. HRR and cylinder pressure traces under different natural gas injection timing operation for −8°and −17° ATDC of pilot injection timing at pilot injection pressure = 72 MPa.

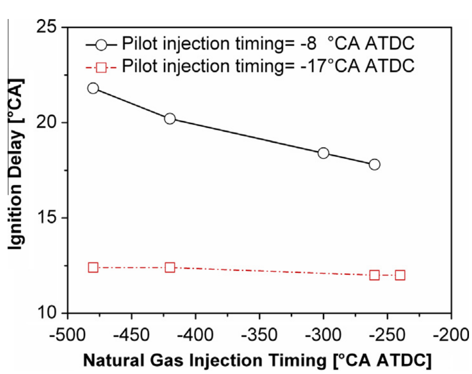

Fig. 9. The ignition delay under different natural gas injection timing operation for −8° and −17° ATDC pilot injection timing at pilot injection pressure = 72 MPa.

dramatically reduced, more than two to three times shorter than that of −8° ATDC operation conditions depending on the natural gas injection timing. With retarded natural gas injection timing, the ignition delay decreased under −8° ATDC pilot injection timing, while the ignition delay is nearly constant under −17° ATDC operation conditions. This is because, under advanced pilot injection timing (−17° ATDC) operation conditions, the ignition combustion is mainly due to the premixed combustion of pilot fuel and the natural gas–air mixture has probably little effect on this process. On the other hand, under the delayed pilot injection timing (−8° ATDC) operation conditions, the temperature of cylinder may be high enough to immediately ignite the pilot diesel as it is injected into cylinder and the ignition process is mostly diffusion-controlled combustion of the diesel pilot.

The combustion duration is also dramatically shortened for advanced pilot injection cases, about 60% shorter compared to the later and more regular timing, as shown in Fig. 10. This faster

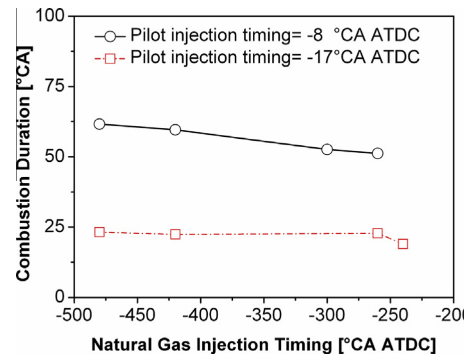

Fig. 10. The combustion duration under different natural gas injection timing operation for −8° and −17° ATDC pilot injection timing at pilot injection pressure = 72 MPa.

burning is attributed to higher premixed-fraction and higher temperature homogeneous combustion. As expected, we find that the combustion duration decreased with retarded natural gas injection timing under both −8° and −17° ATDC operation conditions. This is the evidence that retarded natural gas injection timing enhanced the flame propagation of natural gas combustion.

From the shorter ignition delay, faster combustion and better combustion phasing, we can expect better BTE also. Fig. 11 shows that the BTE of the advanced pilot timing at −17° ATDC is more than 30% better than that of regular pilot injection timing of −8° ATDC. As the timings of both the natural gas port injection and the diesel pilot injection close to each other, the interactions of the mixing become more complicated. For example, at the advanced pilot injection timing case, the ignition delay remains nearly constant with retarded natural gas port injection timing in Fig. 10, but the combustion duration slightly decreases in Fig. 11. Therefore, under −17° ATDC pilot injection timing operation conditions, the BTE is affected by the variation of natural gas injection timing, and does not show a similar trend as previously observed. The advanced pilot fuel injection also produces advanced combustion and a higher charge temperature which is conducive to faster flame propagation of the fuel–air mixture, therefore, the combustion efficiency is expected to get higher and also contributes to higher BTE, which we can confirm by turning attention to the emission results.

3.4. The effects of natural gas injection timing and pilot injection timing on exhaust emissions

Fig. 12 gives the BSTHC, BSNO$_x$ and BSCO emissions versus variation of natural gas injection timing under different pilot injection timings. Under advanced pilot injection timing (−17° ATDC) operation conditions, the BSTHC emissions are much lower, about 50% of the regular pilot injection timing. It also slightly decreased with retarded natural gas injection timing, showing less quenching due to higher charge temperature. It is also consistent with the fact that retarded natural gas injection timing is more conducive to the formation of the stratified-like air–fuel mixture, which is positive for reducing BSTHC emissions. Moreover, higher combustion efficiency achieved under the −17° ATDC pilot injection timing renders the effects of natural gas injection timing variation less significant.

The BSCO data of the advanced pilot injection case shows even better performance than the conventional pilot timing, with approximate 60% reduction. The much lower BSCO is an indication of reduced over-mixing which generally increases CO emissions. As shown in Fig. 12, the BSCO seems insensitive to the variation of natural gas injection timing under −17° ATDC pilot injection

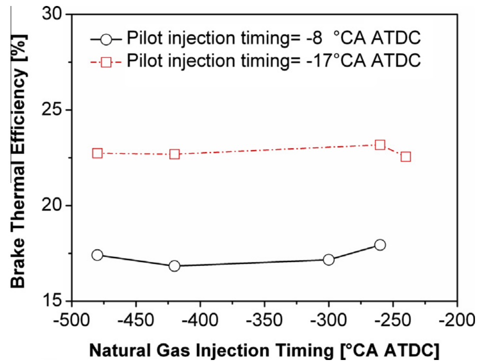

Fig. 11. The BTE under different natural gas injection timing operation for −8° and −17° ATDC pilot injection timing at pilot injection pressure = 72 MPa.

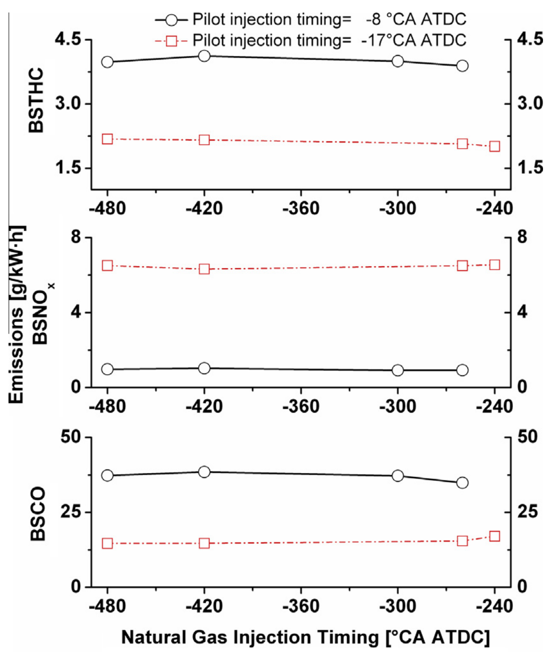

Fig. 12. The BSTHC, $BSNO_x$ and BSCO under different natural gas injection timing operation for −8° and −17° ATDC pilot injection timing at pilot injection pressure = 72 MPa.

timing operation conditions; however, under −8° ATDC cases, the BSCO emissions are reduced by retarding natural gas injection timing. Again, under −17° ATDC cases, the variation of retarded natural gas injection timing has no obvious effects on the BSCO emissions.

The difference between the two pilot injection timings are even more dramatic, but just the opposite with the trends observed for THC and CO emissions. The combustion process under −17° ATDC pilot injection timing operation conditions produce more than six times NO_x emissions compared with the −8° ATDC cases. Both cases show almost no sensitivity with the retarded natural gas injection timing. This is reasonable since $BSNO_x$ is mostly sensitive to combustion temperature.

The PM emissions under different natural gas injection timing operation for −8° and −17° ATDC pilot injection timing at pilot injection pressure = 72 MPa are given in Fig. 13. The PM emissions are significantly lower under −8° and −17° ATDC operation conditions compared with diesel engines, and with advanced pilot injection timing, the PM emissions slightly decreased as shown in Fig. 13. This behavior is probably due to the advance pilot injection

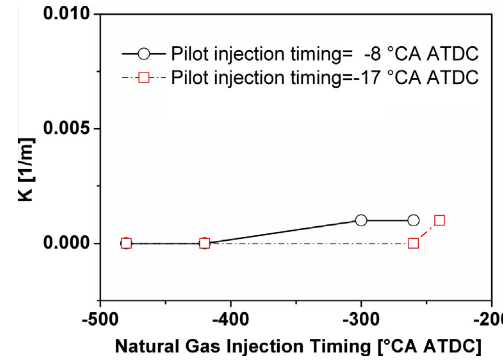

Fig. 13. The PM emissions (expressed in light absorption coefficient or K value) under different natural gas injection timing operation for −8° and −17° ATDC pilot injection timing at pilot injection pressure = 72 MPa.

timing produced higher temperatures and more homogeneous mixtures in the mixing zone, which could reduce PM formation [29]. Moreover, with retarded natural gas injection timing, the PM emissions slightly increased under −8° and −17° ATDC operation conditions. And these results indicated that the stratified mixture provided by retarding natural gas injection timing, enhanced PM emissions due to formation the local over-rich region in cylinder.

4. Conclusions

In the present work, an experimental investigation has been conducted to explore the effects of natural gas injection timing on combustion performance and exhaust emissions of a dual-fuel engine, under 1600 rpm engine speed and low load for different pilot injection pressure and timing operation conditions. The cylinder pressure and the exhaust emissions were recorded during experiments. HRR, ignition delay, combustion duration as well as BTE were calculated. On the basis of the results and discussions presented above, the conclusions can be summarized as following:

(1) The pilot injection parameters (injection timing and pressure) and natural gas injection timing have significant effects on the combustion performance and emissions of the dual-fuel engine under low load operation conditions. The retarded natural gas injection timing improved engine performance at low load in most cases, and higher pilot injection pressure and advanced pilot injection timing obtained better BTE and emissions except for NO_x. Additionally, it seems that it is an effective way to improve the low load performance of the dual-fuel engine by appropriately adjusting natural gas injection timing accompanied with reasonable pilot injection parameters.

(2) Under different pilot injection pressures, the variation of the natural gas injection timing has almost the same impacts on the dual-fuel combustion performance and emissions except for NO_x and PM; under different pilot injection timings, the impacts of natural gas injection timing variation on the dual-fuel combustion performance and emissions are obviously different. Under the later pilot injection timing (−8°CA ATDC), the retarded natural gas injection timing enhanced dual-fuel combustion process and increased BTE as well as decreased THC and CO emissions. However, under the advanced pilot injection timing (−17°CA ATDC), the dual-fuel combustion performance and emissions are not significantly affected by varying the natural gas injection timing.

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