Energy Conversion and Management 87 (2014) 297–304

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental study of the effects of natural gas injection timing on the combustion performance and emissions of a turbocharged common rail dual-fuel engine

Bo Yang [a], Xing Wei [a], Chengxun Xi [a], Yifu Liu [a], Ke Zeng [a,*], Ming-Chia Lai [b]

[a] Xi'an Jiaotong Univ, Sch Energy & Power Engn, Xi'an 710049, PR China
[b] Wayne State Univ, Dept Mech Engn, Detroit, MI 48202, USA

ARTICLE INFO

Article history:
Received 2 April 2014
Accepted 8 July 2014
Available online 30 July 2014

Keywords:
Dual-fuel
Pilot ignited
Natural gas injection timing
Performance
Emissions

ABSTRACT

Natural gas combustion with pilot ignition has been considered to be one of the most promising ways to utilize natural gas in existing diesel engine without serious engine modification and it has been widely researched all over the world. In this study, three experiments of different loads (BMEP 0.240 MPa, 0.480 MPa and 0.767 MPa) were performed on a 2.8 L four-cylinder, natural gas manifold injection dual-fuel engine to investigate the effects of natural gas injection timing on engine combustion performance and emissions. The pilot injection parameters (pilot injection timing and pressure) and natural gas injection pressure remain constant at a speed of 1600 rpm in the experiment. The cylinder pressure, HRR, CoV_{imep}, flame development duration, CA50 and brake thermal efficiency were analyzed. The results indicated that under low and part engine loads, the flame development duration and CA50 can be reduced by properly retarding natural gas injection timing, while the CoV_{imep} increased with retarded natural gas injection timing. As a result, the brake thermal efficiency is increased and the combustion stability slightly deteriorates. Meanwhile, under low and part engine loads, PM emissions in the dual-fuel engine is much lower than that in conventional diesel engines, furthermore, at high load, the PM emissions are near zero. CO and HC emissions are reduced with retarded natural gas injection timing under low and part loads, however, NO_x emissions are slightly increased. Under high load, the flame development duration and CA50 are obviously prolonged with retarded natural gas injection timing companied with a deterioration of brake thermal efficiency. CO and HC emissions are not significantly varied with retarded natural gas injection timing under high load, except that NO_x emissions decreased slightly.

1. Introduction

With increasing concerns about air pollution, more stringent restrictions on vehicle emissions are implemented. The particulate matter (PM) and nitrogen oxides (NO_x) are the major harmful emissions produced by diesel engines. In recent years, many methods have been proposed to simultaneously reduce PM and NO_x emissions in diesel engine. Using alternative fuels and gaseous fuels in existing diesel engine has been proved to be one of the most practical ways to reduce the harmful emissions [1,2]. Consequently, applications of various gaseous fuels on diesel engine have been investigated, such as biogas, synthesis gas, hydrogen and natural gas [2–6]. Moreover, shale gas technical breakthrough provides extra 271 billion cubic meters natural gas production for American in 2013 and the number is believed to be increased in the future all over the world [7]. Natural gas is available in great quantities with considerably cheap price which also has the advantage of low emissions of all carbonaceous emissions. Moreover, due to relatively high auto-ignition temperature of natural gas, the high compression ratio of most conventional direct injection diesel engine can be maintained when natural gas is employed [8]. Concerning the advantage mentioned above of natural gas and the huge number of existing diesel engines, natural gas is likely used as the primary fuel in a dual-fuel engine which is referred to as pilot ignited natural gas dual-fuel engine. For most of the dual-fuel engines, natural gas is usually inducted into the manifold, and then natural gas–air mixture is ignited by a very small amount of diesel-like pilot fuels at the end of the compression stroke. The pilot fuel, acting as an ignition source, is usually directly injected into the cylinder near the top dead center (TDC) [9–11] and diesel, dimethyl ether and biodiesel are the most common fuels that can be used as pilot. It is well

* Corresponding author. Tel.: +86 13609198531.
E-mail address: Kezeng_xjtu@126.com (K. Zeng).

http://dx.doi.org/10.1016/j.enconman.2014.07.030
0196-8904/

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
PES	percent energy substitution
BTE	brake thermal efficiency
CO	nitric oxide
NO_x	nitrogen oxides
THC	total hydrocarbon
BSHC	brake specific HC emissions
BSCO	brake specific CO emissions
$BSNO_x$	brake specific NO_x emissions
PM	particulate matter
CoV_{imep}	coefficient of variation of indicated mean effective pressure
IMEP	Indicated mean effective pressure
λ	excess air ratio
CA50	crank angle where 50% total heat released

known that NO_x and PM emissions can be reduced drastically under dual-fuel operation conditions, with the associated penalty in THC emissions [1,8–10]. In addition to the economic and emissions benefits, diesel/natural gas dual-fuel engine also makes conversion of existing engine relatively simple and maintains full diesel capability in case gaseous fuel is unavailable, both of which are important to bring the technology to market.

In recent years, extensive research has been conducted to investigate the influences of various engine parameters on the performance, combustion and emissions of natural gas/diesel dual-fuel engine. For example, Liu et al. [22] investigated the effects of the pilot fuel quantity on emissions characteristics with optimized pilot injection timing on a premixed dual-fuel engine and they found that the THC emissions reduced significantly with the increase of the pilot diesel quantity. On the contrary, the PM emissions is increased with the increase of the pilot fuel quantity. Papagiannakis et al. [13,14] employed a comprehensive two-zone phenomenological model to examine the effects of pilot fuel quantity and pilot injection timing on dual-fuel engine performance and emissions, and then validated the model with experiment in a premixed dual-fuel engine. They reported that simultaneously increase of the pilot fuel quantity accompanied with an increase of its injection timing results in an improvement of the engine efficiency (increase) and CO emissions (decrease), while it has a negative effect (increase) on NO_x emissions. Nwafor [15] investigated the effect of advanced injection timing on the performance of diesel ignited natural gas dual-fuel engine. And in most cases, they assumed that natural gas–air mixture is homogenous and the effect of stratification of natural gas–air mixture has not been seriously evaluated. But the fact may not be the same with their hypothesis, especially in a manifold injection natural gas dual-fuel engine. Carlucci et al. [16] experimentally investigated the effects of methane supply method combined with variable in-cylinder charge bulk motion and they reported that natural gas port injection can probably induce some stratification effect on the mixture in-cylinder and the stratification of charge is capable to influence combustion flame intensity and propagation inside the combustion chamber. Furthermore, this effect is enhanced when a suitable in-cylinder bulk flow structure is employed; Huang et al. [17] conducted an experiment study on a rapid compression machine to investigate the effect of injection timing on natural gas direct-injection combustion. And they found that early injection timing leads to longer duration of initial combustion while late injection reduces the duration of initial combustion, they believed that this phenomenon is associated with the degree of charge stratification and the intensity of turbulence generated by the fuel jet.

According to previous investigations mentioned above, it can be concluded that the combustion process of dual-fuel engine is significantly influenced by the natural gas–air-pilot fuel mixture and its distribution inside the cylinder. Moreover, the thermal and kinetic interaction between pilot spray and natural gas–air mixture are believed deeply influencing the combustion performance and emissions of dual-fuel engine. Furthermore, natural gas port injection had been proved to influence the combustion flame intensity and propagation of dual-fuel engine due to inducing some stratification effect on the mixture in-cylinder [16]. However, there are few reports focusing on the effects of stratifications on the dual-fuel combustion process. So far, researches about the effect of natural gas injection timing on the combustion and emissions performance of the manifold injection pilot-ignited natural gas dual-fuel engine are still lacking.

In this paper, the author equipped a GW2.8-TC diesel engine with a sequential natural gas manifold injection system in order to operate the diesel engine in dual-fuel mode. Experimental study is conducted to characterize the effects of natural gas injection timing on the combustion performance and emissions (NO_x, HC, CO, and PM) of the dual-fuel engine, with special attention to the combustion performance under low and part engine loads. Moreover, cylinder pressures, flame development duration, CA50, CoV_{imep} and HRR also have been analyzed in this work. The purpose of this paper is to explore the influence of the natural gas injection timing under different operation conditions and to provide the basis for natural gas injection timing optimization in a sequential natural gas manifold injection dual-fuel engine.

2. Experimental set-up and procedure

A four-cylinder, direct injection, turbo-charged, common rail diesel engine manufactured by GREAT WALL Co. in China was used for dual-fuel conversion in this research. The specifications of the original engine are listed in Table 1.

In the experiment, the commercial diesel fuel and natural gas were used and the properties of the fuels are given in Tables 2 and 3.

In order to investigate the effects of natural gas injection timing on engine combustion performance and emissions, a sequential natural gas manifold injection system is adopted. The natural gas injectors are mounted in the intake manifold as close as possible to the intake valve for the purpose of improving the dynamic response of the dual-fuel engine. The schematic diagram of dual-fuel conversion and natural gas fueling system are shown in Fig. 1. The original diesel engine is equipped with a BOSCH common rail injection system including the corresponding supporting ECU. Under dual-fuel operation conditions, the original ECU is retained and a dual-fuel ECU, especially developed for this work, is added to cooperate with the original ECU and the crank shaft signal and cam signal are shared by both ECUs. The pilot and natural

Table 1
Specifications of test engine.

Item	Characteristics	
Type	In-line four-cylinder common rail injection, turbocharged diesel engine	
Combustion chamber	ω type	
Bore X 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

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 (kg/kg)	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

gas injection events are completely controlled by the dual-fuel ECU which has been described in detail in the previous publication [18]. The natural gas supply system is consisted of a high pressure natural gas tank, a two-stage regulator and a shut off solenoid valve. After the regulator, the pressure of natural gas was decreased from maximum pressure about 25 MPa to 0.4 MPa. The gaseous was sequentially injected into intake manifold respectively rather than conventional mixer.

The test engine was coupled with an eddy-current dynamometer. The real-time engine speed, torque, power, exhaust gas and coolant temperatures as well as lubricating oil pressure were monitored by a Powerlink Engine Control System (Type FC2000). The fuel consumption rates of pilot diesel was acquired by a high precision electronic balances with the accuracy of ±0.1 g and the natural gas mass flow rate was measured by a FC2212L gas consumption meter with accuracy of ±0.01 kg/h. Exhaust gas emissions were sampled directly from the exhaust pipe. Total HC, CO, CO_2 and 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 emissions was measured by a Horiba MEXA-600S opacimeter with display resolution of ±0.001 m^{-1}. The in-cylinder pressure was acquired by a Kistler 6055C piezoelectric pressure transducer and 200 continuous cycles with a resolution of 0.2° crank angle (CA) were recorded for combustion performance analysis. Before the start of experiment, the engine was warmed-up under pure diesel operation mode until the coolant temperature reached about 75 °C while the lubricating oil temperature reached 65 °C, and all tests are conducted at ambient temperature about 20 °C.

In the present work, natural gas injection timing is defined as the start injection crank angle at which the natural gas injection signal is sent to natural gas injectors by the dual-fuel ECU. In order to explore the effects of natural gas injection timing on the combustion characteristics and emissions, the natural gas injection timing was varied from −500 °CA to −240 °CA ATDC and the other parameters remain unchanged. The operation conditions of engine, under low-, part- and high-load are summarized in Table 4. The pilot diesel injection timing was fixed at −8 °CA ATDC for the purpose of simultaneous reducing cylinder pressure rise rate and NO_x emissions compared with that under pure diesel operation modes. To present the percent energy substitution (PES), the following expression is employed:

$$\mathrm{PES} = \frac{\dot{m}_{\mathrm{NG}}\mathrm{LHV}_{\mathrm{NG}}}{\dot{m}_{\mathrm{D}}\mathrm{LHV}_{\mathrm{D}} + \dot{m}_{\mathrm{NG}}\mathrm{LHV}_{\mathrm{NG}}} \times 100\% \tag{1}$$

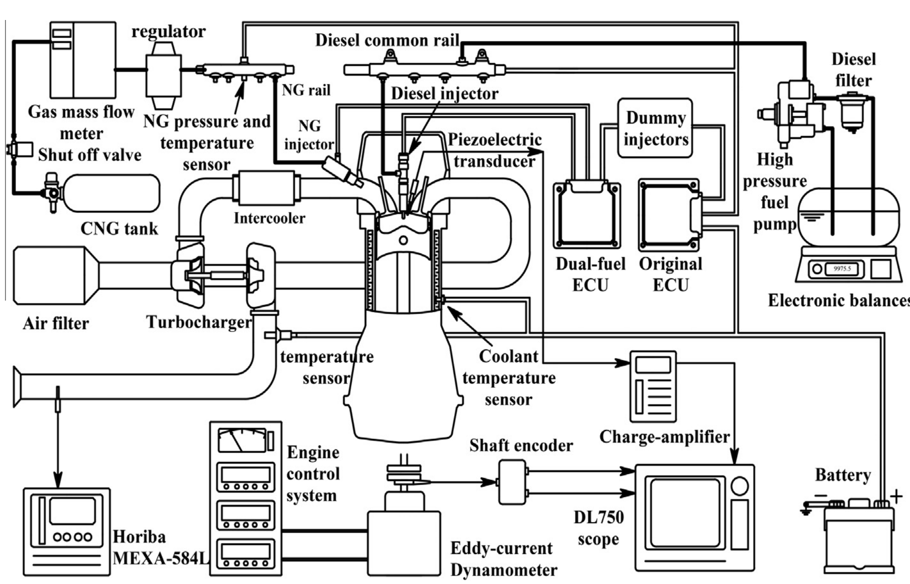

Fig. 1. Engine set-up and instrumentation layout.

Table 4
Engine operating conditions.

Engine speed (r/min) × BMEP (MPa)[c]	Natural gas injection pressure (MPa)	Natural gas flow rate (kg/h)	Pilot fuel common rail pressure (MPa)	Pilot fuel injection quantity (kg/h)	λ	Percent energy substitution (%)
1600 × 0.240	0.4	3.315	72	0.712	2.067	84.470
1600 × 0.480	0.4	4.139	72	0.855	1.850	84.974
1600 × 0.767	0.4	5.082	72	1.129	1.758	84.022

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

3. Results and discussions

To clearly illustrate the effect of natural gas injection timing on the combustion process, the results are provided for typical operation conditions of the three load levels (avoid influencing by valve overlap). Moreover, the flame development duration is defined as the interval crank angles between start of ignition and the crank angle at which 10% mass (pilot diesel and natural gas) fraction burned. In addition, the CoV_{imep} [19] is used to evaluate the combustion stability in this paper and it is defined as

$$CoV_{imep} = \frac{\sigma_{imep}}{\overline{IMEP}} \times 100\% \qquad (2)$$

where σ_{imep} is the standard deviation of IMEP and $\overline{IMEP}$ is the mean value of the IMEP of a specific combustion cycle.

3.1. The effect of natural gas injection timing on the cylinder pressure and heat release

The experimental results of the cylinder pressure and HRR are shown in Figs. 2–4, at the speed of 1600 rpm, with BMEP 0.240 MPa, 0.480 MPa and 0.767 MPa, respectively, under different natural gas injection timings. Observing the heat release curves in Figs. 3–5, the combustion processes can be identified to take place in three stages: the first stage corresponding to the first peak of the HRR curves is the pilot diesel premixed combustion while the second stage corresponds to the natural gas rapid combustion (premixed combustion) and the last stage is the combustion of natural gas–air mixture and the rest of the pilot diesel fuel [1,4,20–22].

At lower loads (BMEP = 0.240 MPa) and part engine loads (BMEP = 0.480 MPa) operation conditions, as shown in Figs. 2 and 3 respectively, with the retarded natural gas injection timing, the cylinder compression pressure increased and the highest cylinder pressure was observed at the latest natural gas injection timing. The results indicated that the compression pressure is affected by the natural gas injection timing 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. Moreover, the first stage of the combustion process was not obviously affected by natural gas injection timing variations; while the second peak of the HRR curves increased with the retarded natural gas injection and the results indicated that the natural gas rapid combustion stage was enhanced and the later diffusion combustion stage decreased with the retarded natural gas injection timing. This is mainly due to the time for natural gas and air mixed is reduced by retarding natural gas injection and there is no enough time to form homogenous charge. Therefore, the later natural gas is injected, the more stratification of natural gas–air mixture is formed and obviously, it seems to have a positive effect to enhance the natural gas combustion rate. More evidence can be found in BMEP = 0.480 MPa compared with BMEP = 0.240 MPa operation conditions. However, at high load (BMEP = 0.767 MPa), as shown in Fig. 4, the cylinder

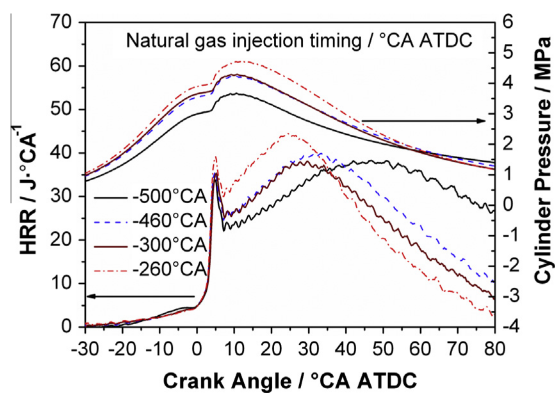

Fig. 2. HRR and cylinder pressure versus natural gas injection timing under BMEP = 0.240 MPa.

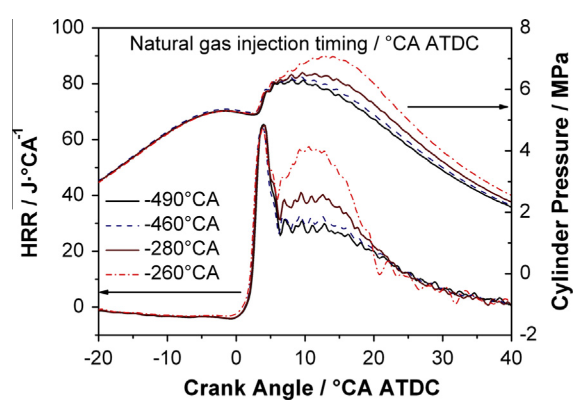

Fig. 3. HRR and cylinder pressure versus natural gas injection timing under BMEP = 0.480 MPa.

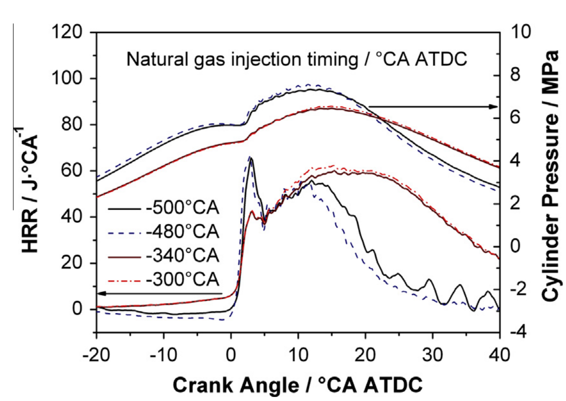

Fig. 4. HRR and cylinder pressure versus natural gas injection timing under BMEP = 0.767 MPa.

pressure curves transformed from a typical two-peak profile to a single-peak profile with the retarded natural gas injection timing and the first peak of the HRR curve (pilot diesel premixed combustion) decreased exceptionally with the retarded natural gas injection timing while the duration of second stage (natural gas rapid combustion) and the third stage increased. This is probably due to retarded the natural gas injection timing reduced the mixture time of natural gas and air and obtained a stratified-like air–fuel mixture in cylinder. However, the stratified-like air–fuel mixture is probably over-rich for ignition kernel formation and combustion flame propagation of the pilot fuel. Consequently, less pilot fuel burned in the first stage and more heat of pilot fuel released during expansion stroke. Moreover, as our expectation, a prolonged combustion process is observed in Fig. 4 at high loads with retarded natural gas injection timing.

3.2. The effect of natural gas injection timing on the combustion performance

As far as flame development duration is concerned (Fig. 5), we observe that the flame development duration is decreased with the retarded natural gas injection timing at low load (BMEP = 0.240 MPa) and part engine load (BMEP = 0.480 MPa), while at high load (BMEP = 0.767 MPa), the flame development duration is increased with the retarded natural gas injection timing. It reveals that the stratification of natural gas–air mixture is better for pilot ignition and natural gas flame propagation at low and part engine loads, especially at low load. The natural gas-air mixture is usually over lean and it is difficult to be ignited by the pilot fuel at low load, while retarded natural gas injection timing products a local rich mixture, and consequently, the natural gas rapid combustion stage is enhanced with retarded natural gas injection timing as we observed in Figs. 2 and 3. Therefore, the flame development duration is reduced at low and part engine loads. However, at high load, the flame development duration is relatively increased with the retarded natural gas injection timing. This is due to stratification of mixture at high load may lead to over-rich regions and that may slow down the initialization of the ignition source and flame kernel formation [23].

Observing the CA50 curves in Fig. 6, retarded natural gas injection timing provides a local rich and stratification mixture. Obviously, the flame spread speed is accelerated and the CA50 becomes closer to the TDC at low and part engine loads. However, at high load, the CA50 is remote from the TDC with retarded natural gas injection timing and this is probably related to local over-rich mixture which has a negative effect on the natural gas ignition and flame propagation.

The brake thermal efficiency is increased with the retarded natural gas injection timing at low and part engine loads as shown in Fig. 7, especially at low load. The maximum increased value is 16% compared with the minimum one. However, the curves of thermal efficiency decreased slightly at high load with the retarded natural gas injection timing. The results indicated that retarded natural gas injection timing probably obtained a stratified-like air–fuel mixture, which reduced over lean regions and enhanced the kernel formation and flame propagation of pilot ignition sources at low and part loads. But at high load, the same stratified-like air–fuel mixture probably produced over-rich regions in cylinder for the ignition kernel formation and flame propagation of pilot ignition sources. This probably slowed down the combustion process. As a result, the flame development duration and the CA50 are prolonged with retarded natural gas injection timing. Additionally, more pilot diesel burned during expansion stroke which is in accordance with the results of flame development duration and CA50.

The variation of CoV_{imep} with retarded natural gas injection timing is provided in Fig. 8. At low and part loads, with retarded

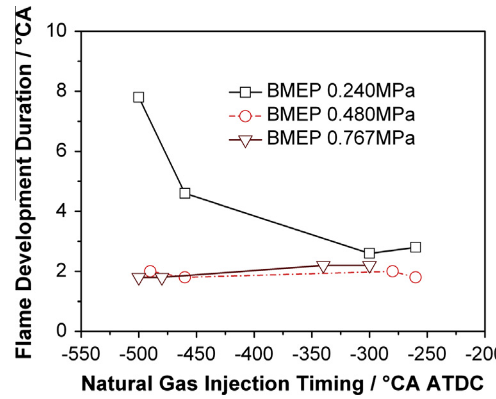

Fig. 5. Flame development duration versus natural gas injection timing under different loads.

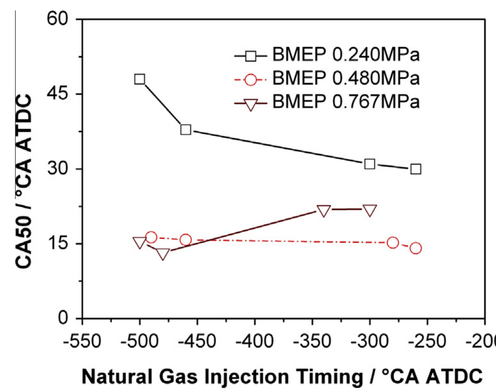

Fig. 6. CA50 versus natural gas injection timing under different loads.

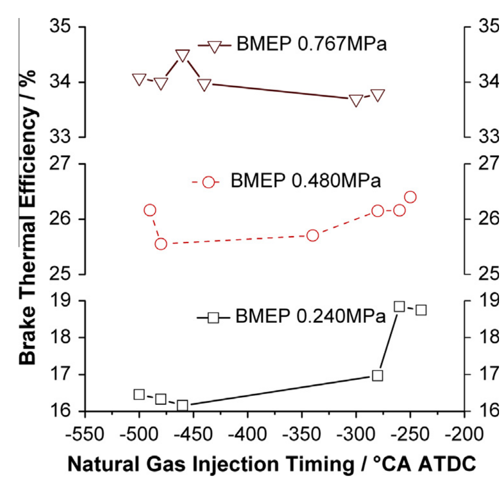

Fig. 7. Brake thermal efficiency versus natural gas injection timing under different loads.

natural gas injection timing, the CoV_{imep} slightly increased at early injection timings and then dramatically deteriorated at the latest injection timings. The maximum value of the CoV_{imep} is more than 7%; however, at high loads, the values of CoV_{imep} are no more than 2% and the variation does not show a univocal behavior. The results indicated that combustion stability probably deteriorated at low and part loads due to over stratification of mixture obtained by retarding natural gas injection timing, especially at very later

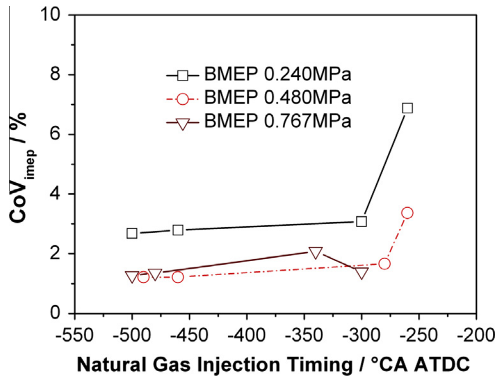

Fig. 8. CoV_{imep} versus natural gas injection timing under different loads.

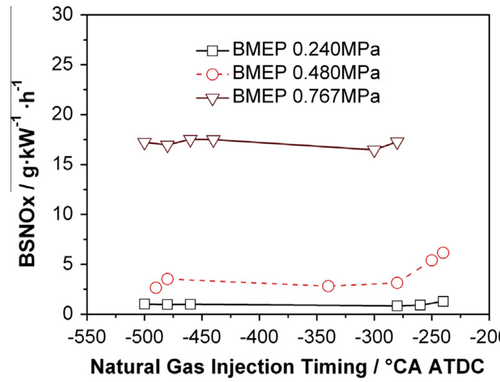

Fig. 11. $BSNO_x$ emissions versus natural gas injection timing under different loads.

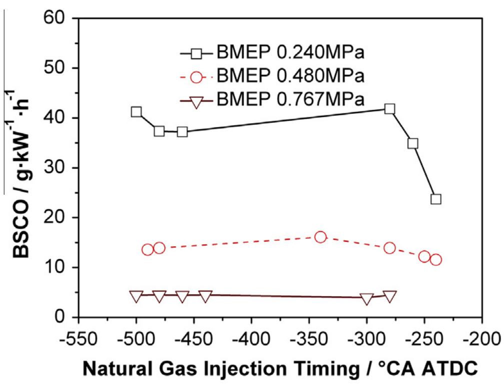

Fig. 9. BSCO emissions versus natural gas injection timing under different loads.

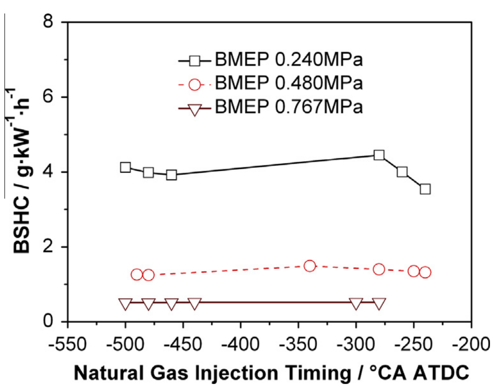

Fig. 10. BSHC emissions versus natural gas injection timing under different loads.

injection timing. At high loads, the cyclic variation is very small and slightly affected by the natural gas injection timing. This is probably explained by the over all richer mixture in cylinder and the stability of combustion is not significantly affected by the mixture stratification at high loads.

3.3. The effect of natural gas injection timing on emissions

The brake specific CO emissions are a function of the air/fuel ratio and the charge temperature, which control the fuel's oxidation and decomposition [19,24,25]. At low and part engine loads, the temperature of mixture is increased with retarded natural gas injection timing due to shorter time left to natural gas mix with air. Moreover, the variation of natural gas injection timing also provides stratification mixture and this improves utilization of natural gas during the second stage of combustion (natural gas premixed combustion). Therefore, as we observed in Fig. 9, the BSCO decreased with retarded natural gas injection timing under low and part engine loads. However, under high engine loads, the BSCO emissions slightly varied and did not show a univocal behavior. This is probably due to high fuel/air ratio compared with that under low and part engine loads and therefore, the variation of natural gas injection timing has no obviously effects on it.

HC emissions are primarily produced by incomplete combustion and lower combustion rates in dual-fuel operation conditions. Moreover, Liu et al. [12] experimentally validated that around 90% of the HC emissions in dual-fuel operation conditions were composed by the unburned methane. This is due to much higher octane number of natural gas than that of diesel fuel and natural gas has lower flame propagation speed compared to diesel fuel. Therefore, retarded natural gas injection timing improves the natural gas combustion process and accelerates the flame propagation speed under lean mixture operation conditions. Thus, as shown in Fig. 10, the BSHC emissions decreased with retarded natural gas injection timing under low and part engine loads. However, the similar variation is not observed under high load and it can be explained by that the combustion temperature is high enough for HC oxidation and the variation of natural gas injection timing has no significant effects on accelerating natural gas flame propagation under high engine load.

Formation of NO_x emissions are directly related to the peak temperature of combustion and in dual-fuel operation condition, NO_x emissions mainly come from the pilot diesel combustion. Fig. 11 gives $BSNO_x$ emissions curves under different loads and the results indicated that NO_x emissions increased with retarded natural gas injection timing under low and part engine loads while slightly decreased under high load. This trend is in accordance with HRR curves shown in Figs. 2–4. Retarded natural gas injection timing at low and part loads leads to more natural gas entrained in the spray of pilot diesel and enhances the combustion of pilot diesel. So NO_x emissions are slightly deteriorated at low and part loads. But under high loads, with retarded natural gas injection timing, a stratified-like air–fuel mixture is produced in-cylinder and over-rich regions are likely to be formed. As a result, the flame development duration and CA50 are prolonged. More heat released during expansion stroke and the combustion temperature is progressively decreased. Therefore, NO_x emissions slightly decreased with retarded natural gas injection timing at high loads.

Fig. 12 shows that PM emissions slightly increased with retarded natural gas injection timing at low load. However, at part and high loads, the PM emissions are near zero and seems insensitive to the variation of natural gas injection timing. Generally speaking, the value of the PM emissions are much lower all over

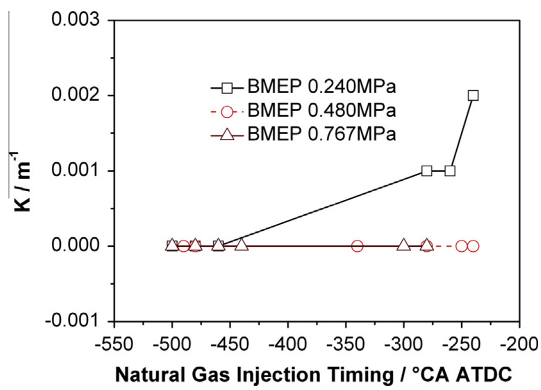

Fig. 12. PM emissions (expressed in light absorption coefficient or *K* value) versus natural gas injection timing under different loads.

the entire operation range compared with that in conventional diesel operation conditions. This is mainly due to the primary component of natural gas is methane (CH_4) which is a lower member in the paraffin family, and has a smaller tendency to produce particulate matter [26]. Secondly, at low load, the flame development duration reduced with retarded natural gas injection timing and the diesel–air mixed is deteriorated. So PM emissions increased with retarded natural gas injection timing [27].

4. Conclusions

The effects of natural gas injection timing on combustion performance and emissions were experimentally investigated on a four-cylinder, manifold sequential injection natural gas dual-fuel engine and the results of the investigation are summarized as following:

(1) An improvement in BTE under low and part engine loads is achieved by employing later natural gas injection timing, especially at low load. The maximum increase of BTE gets up to 16% compared with the minimum one. Moreover, under high engine load, the earlier natural gas injection timing should be adopted to get a better BTE. Additionally, with increased engine loads, the BTE is consistently increased and the highest BTE is obtained at earlier natural gas injection timing under high load.

(2) Retarded natural gas injection timing under low and part engine loads could enhance flame propagation and improve natural gas combustion efficiency. Consequently, the flame development duration and CA50 are reduced while the combustion stability represented by CoV_{imep} is slightly deteriorated. However, retarded natural gas injection timing under high engine load has a negative impact on the combustion performance.

(3) As far as emissions are concerned, BSCO and BSHC decreased with retarded natural gas injection timing under low and part engine loads. However, under high load, both BSCO and BSHC are not significantly influenced by natural gas injection timing variation. $BSNO_x$ emissions increased under low and part engine loads while slightly decreased under high loads with retarded natural gas injection timing. Additionally, the PM emissions are very low in dual fuel operation mode and near zero at high load. Overall, it is not sensitive to natural gas injection timing except for a slightly increased at low load.

(4) The combustion performance and emissions can be significantly improved by adjusting natural gas injection timing according to different operation conditions and it appears that the optimum natural gas injection timing accompanied with reasonable pilot injection parameters can be a potential tool to improve dual-fuel engine combustion performance and emissions.

Acknowledgment

This study is financially supported by the National Basic Program of China (Program 973) (Grant No. 2011CB707200).

References

[1] Wagemakers AMLM, Leermakers CAJ. Review on the effects of dual-fuel operation, using diesel and gaseous fuels, on emissions and performance. SAE Technical Paper, 2012-01-0869, 2012, http://dx.doi.org/10.4271/2012-01-0869.
[2] Sahoo BB, Sahoo N, Saha UK. Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines—A critical review. Renew Sustain Energy Rev 2009;13(6–7):1151–84. http://dx.doi.org/10.1016/j.rser.2008.08.003.
[3] Selim MYE. Effect of engine parameters and gaseous fuel type on the cyclic variability of dual fuel engines. Fuel 2005;84(7–8):961–71. http://dx.doi.org/10.1016/j.fuel.2004.11.023.
[4] Elnajjar E, Selim MYE, Hamdan MO. Experimental study of dual fuel engine performance using variable LPG composition and engine parameters. Energy Convers Manage 2013;76:32–42. http://dx.doi.org/10.1016/j.enconman.2013.06.050.
[5] Bilcan A, LeCorre O, Tazerout M, et al. Characterization of the LPG – diesel dual fuel combustion. SAE Technical Paper, 2001-28-0036, 2001.
[6] Lata DB, Misra A, Medhekar S. Investigations on the combustion parameters of a dual fuel diesel engine with hydrogen and LPG as secondary fuels. Int J Hydrogen Energy 2011;36(21):13808–19. http://dx.doi.org/10.1016/j.ijhydene.2011.07.142.
[7] Petroleum B. BP 2013 Statistical review of world energy. London 2013. <http://www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013.html>. [accessed on 20.05.14].
[8] Papagiannakis RG, Rakopoulos CD, Hountalas DT, et al. Emission characteristics of high speed, dual fuel, compression ignition engine operating in a wide range of natural gas/diesel fuel proportions. Fuel 2010;89(7):1397–406. http://dx.doi.org/10.1016/j.fuel.2009.11.001.
[9] Ryu K. Effects of pilot injection pressure on the combustion and emissions characteristics in a diesel engine using biodiesel–CNG dual fuel. Energy Convers Manage 2013;76:506–16. http://dx.doi.org/10.1016/j.enconman.2013.07.085.
[10] Carlucci AP, de Risi A, Laforgia D. Experimental investigation and combustion analysis of a direct injection dual-fuel diesel–natural gas engine. Energy 2008;33(2):256–63. http://dx.doi.org/10.1016/j.energy.2007.06.005.
[11] Nwafor OMI. Effect of choice of pilot fuel on the performance of natural gas in diesel engines. Renewable Energy 2000;21(3–4):495–504.
[12] Liu J, Yang FY, Wang HW, et al. Effects of pilot fuel quantity on the emissions characteristics of a CNG/diesel dual fuel engine with optimized pilot injection timing. Appl Energy 2013;110:201–6. http://dx.doi.org/10.1016/j.apenergy.2013.03.024.
[13] Papagiannakis RG, Hountalas DT, Kotsiopoulos PN. Experimental and theoretical analysis of the combustion and pollutants formation mechanisms in dual fuel DI diesel engines. SAE Technical Paper, 2005-01-1726, http://dx.doi.org/10.4271/2005-01-1726.
[14] Papagiannakis RG, Hountalas DT, Rakopoulos CD. Theoretical study of the effects of pilot fuel quantity and its injection timing on the performance and emissions of a dual fuel diesel engine. Energy Convers Manage 2007;48(11):2951–61. http://dx.doi.org/10.1016/j.enconman.2007.07.003.
[15] Nwafor OMI. Effect of advanced injection timing on the performance of natural gas in diesel engines. SaÅdhanaÅ 2000;25(1):11–20.
[16] Carlucci AP, Laforgia Domenico, Saracino Roberto, et al. Combustion and emissions control in diesel–methane dual fuel engines: the effects of methane supply method combined with variable in-cylinder charge bulk motion. Energy Convers Manage 2011;52(8–9):3004–17. http://dx.doi.org/10.1016/j.enconman.2011.04.012.
[17] Huang Z, Shiga S, Ueda T, et al. Effect of fuel injection timing relative to ignition timing on the natural–gas direct-injection combustion. J Eng Gas Turbines Power 2003;125(3):783–90. http://dx.doi.org/10.1115/1.1563243.
[18] Yang B, Wei X, Zeng K, et al. The development of an electronic control unit for a high pressure common rail diesel/natural gas dual-fuel engine. SAE Technical Paper, 2014-01-1168, 2014, http://dx.doi.org/10.4271/2014-01-1168.
[19] Heywood JB, Internal combustion engine fundamentals, McGraw-Hill international edition, Singapore, ISBN 0-07-100499-8.
[20] Alla GHA, Soliman HA, Badr OA, et al. Effect of injection timing on the performance of a dual fuel engine. Energy Convers Manage 2002;43(2):269–77.
[21] Selim MYE. Pressure–time characteristics in diesel engine fueled with natural gas. Renewable Energy 2001;22(4):473–89.

[22] Bilcan A, Le Corre O, Tazerout, et al. Characterization of the LPG – diesel dual fuel combustion. SAE Technical Paper 2001-28-0036, 2001, http://dx.doi.org/10.4271/2001-28-0036.
[23] Liu YF, Liu B, Liu L, et al. Combustion characteristics and particulate emission in a natural–gas direct-injection engine: effects of the injection timing and the spark timing. Proc Inst Mech Eng Part D: J. Automobile Eng 2010; 224(8):1071–80. http://dx.doi.org/10.1243/09544070JAUTO1532.
[24] Srinivasan KK, Krishnan SR, Midkiff KC. Improving low load combustion, stability and emissions in pilot-ignited natural gas engines. Proc Inst Mech Eng Part D: J Automobile Eng 2006;220(D2):229–39. http://dx.doi.org/10.1243/09544070JAUTO104.
[25] Krishnan SR, Srinivasan KK, Singh S, et al. Strategies for reduced NO_x emissions in pilot-ignited natural gas engines. J Eng Gas Turbines Power-Trans ASME 2004;126(3):665–71. http://dx.doi.org/10.1115/1.1760530.
[26] Papagianakkis RG, Hountalas DT. Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot diesel fuel and natural gas. Energy Convers Manage 2004;45(2):2971–87. http://dx.doi.org/10.1016/j.enconman.2004.01.013.
[27] Shen J, Qin J, Yao M. Turbocharged diesel/CNG dual-fuel engines with intercooler: combustion, emissions and performance. SAE Technical Paper, 2003-01-3082, 2003, http://dx.doi.org/10.4271/2003-01-3082.