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Effects of pilot fuel quantity on the emissions characteristics of a CNG/diesel dual fuel engine with optimized pilot injection timing

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HIGHLIGHTS

- Emission characteristics of the CNG/diesel dual fuel engine.
- NO*x* emissions averagely reduced by 30%.
- The unburned HC emissions are obviously higher.
- Around 90% of the THC emissions were unburned methane.
- PM was increased with the increase of pilot diesel quantity.

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ABSTRACT

For CNG/diesel dual fuel engines, the effects of pilot fuel quantity and injection timing are noticeable and significant. In this study, the emission characteristics of a CNG–diesel dual fuel engine with different pilot diesel fuel quantity and optimized pilot injection timing were investigated. The CO emission levels under dual fuel mode are considerably higher than that under normal diesel operation modes even at high load, which indicated that there exist some flame extinction regions. Dual fuel mode reduces NO*x* emissions by 30% averagely in comparison to diesel mode. That is because most of the fuel is burned under lean premixed conditions which result in lower local temperature. The unburned HC emissions under dual-fuel mode are obviously higher than that of the normal diesel mode, especially at low to medium loads. And around 90% of the THC emissions were unburned methane, which means the flame does not propagate throughout the charge. THC emissions reduce significantly with the increase of the pilot diesel quantity. Thanks to the premixed nature of the combustion mode and the methane molecular structure, the PM emission is reduced obviously under dual fueling condition. The PM emission is increased with the increase of the pilot fuel quantity.

1. Introduction

With rising fuel price and more stringent emission legislation, recent researches are focus on high efficiency and low emissions technologies in the field of internal combustion engines [1]. In order to simultaneously reduce soot and NO*x* emissions while achieving high thermal efficiency, many strategies have been proposed in compression ignition (CI) engine. The low temperature premixed combustion is employed by most of the strategies, and the ultimate goal is to achieve Homogeneous Charge Compression Ignition (HCCI) combustion with near zero NO*x* and soot emissions [2,3]. However, the controllability of the heat release rate and the ignition timing is the challenge of the HCCI concept.

In order to address these problems, dual fuel combustion concept was utilized by many researchers. With port injection of a low-reactivity fuel combining direct in-cylinder injection of a high-reactivity fuel, the combustion phasing and duration can be flexibly controlled through reactivity gradient [4–7]. A higher octane number (ON) indicates a higher resistance to auto-ignition, which in turn can effectively extend the upper load limit of the dual fuel engine without using too much EGR. From this point of view, natural gas with large proven reserves and high ON is the best choice of the port injection fuel.

The study of Papagiannakis et al. shows that the maximum explosion pressure of the diesel ignited natural gas engine is lower than that of the original diesel engine. And at high loads, the combustion duration is shorter than that of the original diesel engine [8]. NO*x* and soot emissions are lower compared with the original diesel engine [9–11]. At Low loads, however, the diesel ignited natural gas engine has higher CO and unburned HC emissions [12,13].

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Through the intake air throttle valve and EGR valve controlling the air–fuel ratio of the diesel-ignited natural gas engine, the emission characteristics of the diesel ignited natural gas engine at low load can be improved significantly [14,15]. By changing the EGR rate and fuel injection timing to generate a two-stage ignition, a higher thermal efficiency and lower NO*x* emissions can be obtained [16].

However, it is not well known how to optimize the exhaust emission characteristics of natural gas engines through combinations of the different performance parameters (such as premixed equivalence ratio, pilot fuel quantity and pilot injection timing for dual-fuel CI engines). And rare studies have mentioned the methane emission characteristics. In order to optimize the emission characteristics, more studies are required to investigate how to change the quantity and injection timing of the pilot fuel at different engine loads.

The objective of this study is to investigate the emissions characteristics of a CNG/diesel dual fuel engine with different pilot fuel amounts and injection timing. The methane emission characteristics are also studied.

2. Experimental apparatus and setup

2.1. Test engine

The original engine was a multi cylinder, direct injection, turbocharged with common rail system diesel engine manufactured by WEICHAI POWER in China. A summary of the engine's specification is listed in Table 1.

Table 1
Summary of engine specification.

Bore × Stroke	126 × 130 mm
Number of cylinders	6
Displacement	9.726 L
Maximum torque/speed	1250 N m/1200–1600 rpm
Rated power/speed	247 kW/2200 rpm
Compression ratio	17.0
Number of injector nozzle holes	7
Injector nozzle spray angle	146
Exhaust vale closing timing	21 °CA ATDC
Inlet valve opening timing	20 °CA ATDC

2.2. Dual fuel conversion method

The dual fuel engine conversion and gas fueling system is shown in Fig. 1. The original electronic control unit (ECU) was retained. A fully functional dual fuel ECU was designed and built in Tsinghua University using copyrighted software developed in-house. The dual fuel ECU was designed to control diesel fuel injection pulse width, start of injection and CNG flow rate, while monitoring engine temperatures and pressures for safety and data logging purposes. The dual fuel ECU is designed to switch the engine immediately to full diesel operation in the event of an irregularity. Under dual fuel running conditions, the diesel and CNG injections were controlled by the dual fuel ECU, and the diesel injection command of the original ECU is applied to the dummy load which simulates the solenoid injector.

The gas fueling system consisted of high pressure natural gas bottles, a shut off valve, a high pressure filter, a natural gas flow meter, a coolant heated pressure regulator. After the regulator, the pressure of natural gas was decompressed from 18 MPa to 0.8 MPa. The amount of natural gas was changed through controlling the fuel injection duration of four SP010A CNG injectors mounted on the gas rail. The gas rail pressure and fuel temperature was also recorded. A simple venturi type gas mixer was installed at a distance of ten pipe diameters upstream of the inlet manifold to ensure complete mixing of the air and fuel was achieved.

The emissions of nitric oxides (NO*x*), total hydrocarbon (THC) and carbon monoxide (CO) were detected by a Horiba MEXA7100-DEGR analyzer with chemiluminescent detector (CLD), flame ionization detector (FID) and non-dispersive infrared analyzer (NDIR), respectively. An ONOSOKKO FZ2100 coriolis mass flow meter was used to measure diesel fuel mass flow rate. The airflow rate was measured with a SENSYFLOW hot-film air flow meter. The CNG flow rate was measured by a BROOKS gas flow meter.

2.3. Test fuels

The engine is fueled with commercial 0# diesel fuel and natural gas obtained from the local distribution network in Beijing City. The detailed specifications of the two fuels are listed in Table 2.

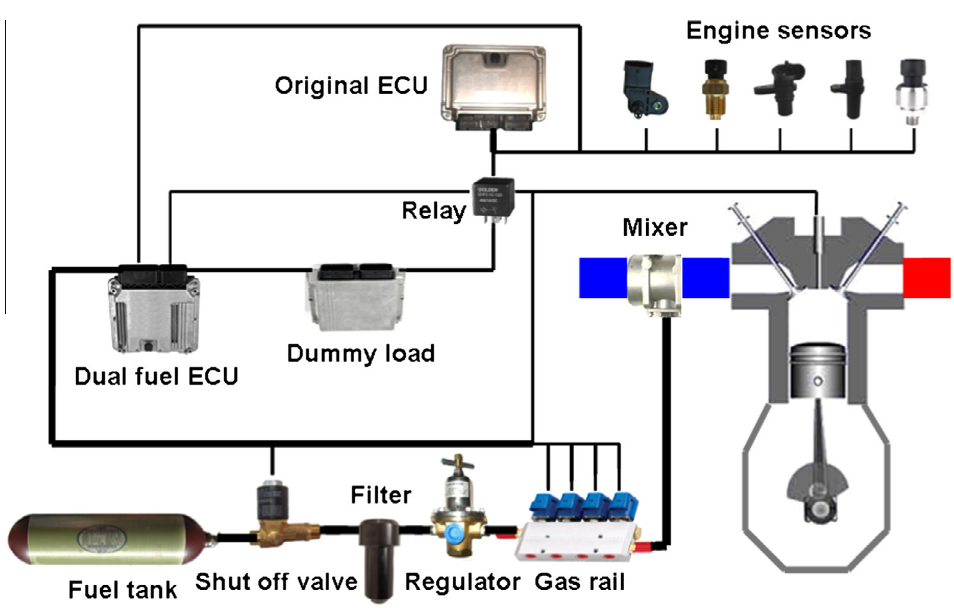

Fig. 1. Dual fuel engine conversion and gas fueling system.

Table 2
Fuel properties.

CNG		0# diesel	
Methane	96.51% v/v	Cetane number	52.6
Ethane	1.2% v/v	Density	833.7 kg/m^3
Propane	0.18% v/v	Lower heat value	42.74 MJ/kg
Butane	0.04% v/v	Stoichiometric air–fuel ratio	14.5 kg/kg
Iso-pentane	0.01% v/v	Sulfer?	
Oxygen	0.01% v/v		
Nitrogen	0.22% v/v		
Carbon dioxide	1.81% v/v		
Lower heat value	50.9 MJ/kg		
Stoichiometric air–fuel ratio	16.88 kg/kg		

Table 3
Tested fuel flow rate and pilot fuel injection timing.

Engine speed (r/min)	CNG flow rates (kg/h)	Pilot fuel injection rate (kg/h)	Injection timing (°CA BTDC)
1320	17.99	0.8	12.5
		5.2	8.0
		16.0	5.0
1627	22.22	0.6	15.0
		4.7	11.0
		15.5	7.0
1933	25.55	1.9	17.0
		9.9	12.0
		18.3	9.0

2.4. Test method and uncertainty

Before test, the engine was warmed-up in original diesel mode until the coolant temperature varied from 75 °C to 80 °C while the lubricating oil temperature reached 65 °C. All tests were conducted at ambient temperature of approx. 23 °C, and the charged air temperature after the intercooler is controlled below 40 °C.

According to the ESC test method, three engine speeds of 1320 r/min, 1627 r/min and 1933 r/min were chosen and the power percentages were set to be 50%, 75% and 100%. For dual-fuelling operation, the load was controlled by adjusting the injection rate and timing of the pilot diesel. The natural gas flow rates were fixed at each speed. The corresponding mass flow rates of the premixed CNG and the injection rates of the pilot fuel with optimized injection timings were shown in Table 3.

3. Results and discussions

This section presents engine emissions characteristics that were studied experimentally through different operating modes. Three engine speeds of 1320 r/min, 1627 r/min and 1933 r/min were chosen and the power percentages were set to be 50%, 75% and 100%. At each test condition, experiments were carried out with pure diesel and dual fuel operation modes. Comparison parameters for different operation modes were conducted.

3.1. Excess air ratio

The excess air ratio significantly influences the combustion process and the emission characters. Fig. 2 illustrates the premixed and total excess air ratios, which are calculated with the following expressions:

$$\lambda_{premix} = l/l_{0\,CNG}$$

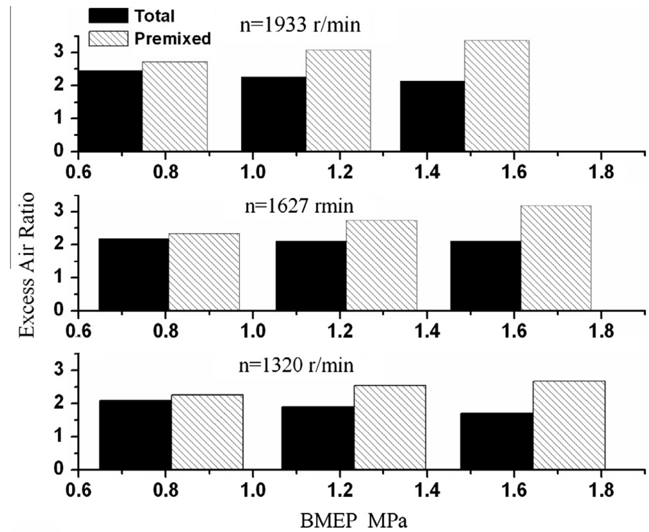

Fig. 2. Premixed and total excess air ratios.

$$\lambda_{total} = l/l_{0\,total}$$

where l is the actual air mass, $l_{0\,CNG}$ is the stoichiometric air/fuel ratio of the premixed CNG, $l_{0\,total}$ is the total stoichiometric air/fuel ratio of the premixed CNG and diesel.

It can be seen that the total excess air ratio is decreased with the increase of BMEP. However, the premixed excess air ratio is increased with the increase of load. That is because the inlet air pressure is increased due to the higher boost effect at high loads.

3.2. CO emission characteristics

Due to the lack of oxygen, the combustion is incomplete in the over rich region, which result in higher CO formation. However, in the fuel lean region, when the combustion temperature is under 1450 K, it is also generated a large number of CO [17]. This temperature is also the limited temperature of the flame extinction [18]. There are three main reasons for the generation of CO: first, the temperature of the reaction mixture is suddenly too low; second, suddenly lack of oxidant; finally, the suitable reaction time is too short.

Fig. 3 illustrates the CO emission characteristics with pure diesel and dual fuel operation mode. It can be seen that the CO emission levels under dual fuel mode are considerably higher than their values corresponding to normal diesel operation conditions, which indicated that there exist some flame extinction regions, even at high load. Therefore, most of the CO emission is from the incomplete oxidation of the premixed CNG. When operating with lean premixed mixtures at light load, most of the energy release comes from the combustion of the pilot diesel and the gaseous fuel entrained within its envelope. The mixture in the peripheral zones of the injection spray is too lean to sustain the flame propagation. Due to this, the local temperature falls and freezes the reactions of CO oxidation. Under high load conditions, the increase of the pilot quantity improves the pilot fuel spray characteristics, which increases the number of ignition centers. And the unburned mixture is compressed to a higher temperature with larger pilot energy release. Moreover, the intake pressure and temperature is higher, which lead to a higher in-cylinder compression temperature. So, more premixed fuel can be oxidized completely. However, cold wall quenching may become the primary source of the high CO emissions. With the increase of the engine speed, less time is left to complete the CO to CO_2 reactions before the local temperature

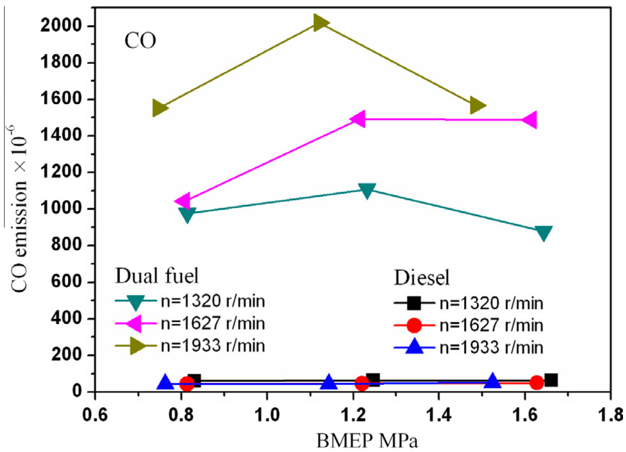

Fig. 3. CO emission characteristics.

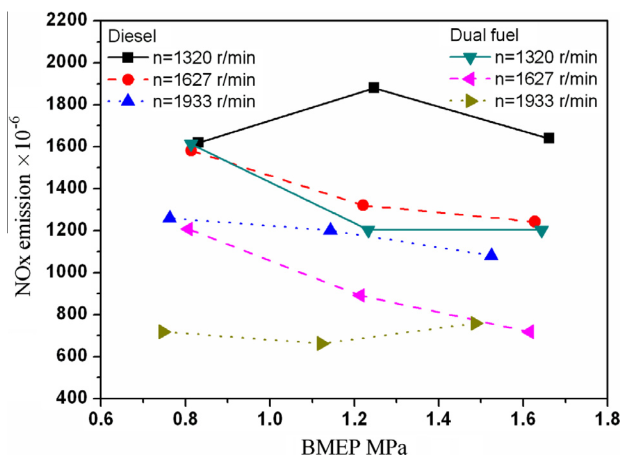

Fig. 4. NO*x* emission characteristics.

below freeze temperature during expansion stroke which increases the CO emissions.

3.3. NOx emission characteristics

NO*x* is formed in greater quantity with high peak combustion temperatures, sufficiently high oxygen concentrations and long residence time. Significant NO is produced when the local temperature is above 2000 K for mixtures at or below stoichiometric. The variations of NO*x* emissions for diesel and dual fuel mode at engine loads and speeds are shown in Fig. 4. Dual fuel mode shows greater NO*x* emission reductions in comparison to diesel mode, which is more obviously at high load. Dual fuel mode averagely reduces NO*x* emissions by 30% in comparison to diesel mode. That is because most of the fuel is burned under lean premixed conditions which result in lower local temperature. At high load operation conditions, the pilot fuel injection timing is retarded to reduce the risk of knock, which leads to a reduction of the NO*x* emissions. With the increase of the engine speed, the NO*x* emissions reduced, that is because there is less residence time for the NO formation.

3.4. THC emission characteristics

The HC formation condition is almost similar to that of the CO. However, the temperature of near complete oxidation of HCs is lower, which has been found to be around 1200 K with independence of

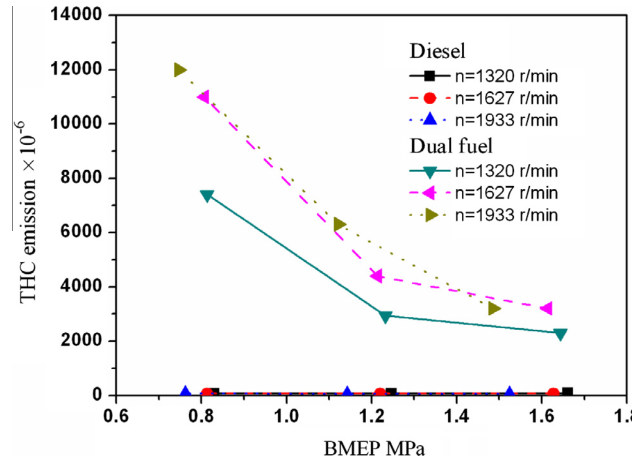

Fig. 5. THC emission characteristics.

the original fuel type. Generally, under low to moderate load operation condition, the HC emissions of the dual fuel engine were significantly higher than that of the original diesel engine. [19–21].

Fig. 5 indicates HC concentrations of over than 10,000 ppm at low to medium loads, compared with significantly less than 100 ppm in conventional diesel operation conditions. As shown in Fig. 6, around 90% of the THC emissions were composed by unburned methane. There are three main reasons for this phenomenon. Firstly, flame quenching. When the flame approach the combustion chamber wall, the temperature of the mixture is too low to complete the combustion leaving a layer of unburned mixture. Secondly, some of the mixture is compressed into the crevices of the combustion chamber during the compression stroke, which misses the primary combustion process. Finally, the mixture is too fuel-lean for combustion to propagate throughout the charge.

At high load operation conditions with the increase of the pilot quantity, THC emissions reduce significantly which is expected due to a number of contributing factors. First, the ignition energy is increased. Second, the pilot fuel spray atomization characteristic is improved. Third, the turbulence intensity is enhanced with higher injection energy. Fourth, the number of the ignition center is increased. Fifth, the pilot fuel spray envelope is extended. Sixth, the heat transfer to the unburned mixture is increased. Seventh, the compression effect to the unburned premixed mixture is enhanced [22]. Furthermore, at high load the boost pressure and temperature is higher, which lead to an increased in-cylinder compression temperature. All of these effects reduce the combustion limits of the lean premixed CNG fuel and increase the flame propagation speed. So, more premixed CNG participates in the combustion process. However, the THC concentrations are still higher than 2000 ppm at full load conditions. With the increase of engine speed, there is less residence time for the fuel oxidation, which results in higher THC emissions.

3.5. PM emission characteristics

According to the research of Kitamura et al. [17], Soot is formed obviously when the local equivalence ratios larger than 2 and the temperature between 1600 K and 2500 K. The smoke emission of the dual fuel mode is significantly lower than that of the diesel engine, as shown in Fig. 7. Methane, the primary constituent of CNG, has no carbon–carbon bonds with high hydrogen to carbon ratio, which lead to lower sooting tendencies [23]. Furthermore, the natural gas has enough residence time in traveling from the intake manifold to the combustion chamber to form a well mixed mixture prior to combustion. Therefore any emitted particulates are formed

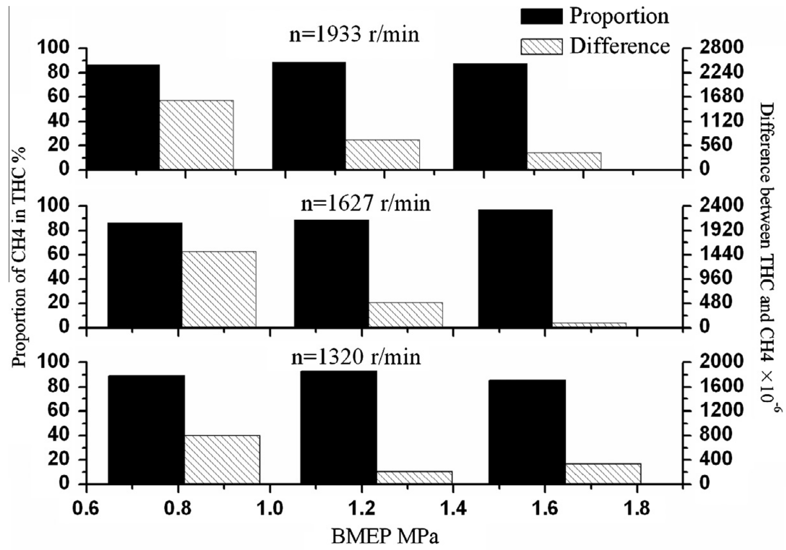

Fig. 6. Proportion of CH_4 in THC emissions.

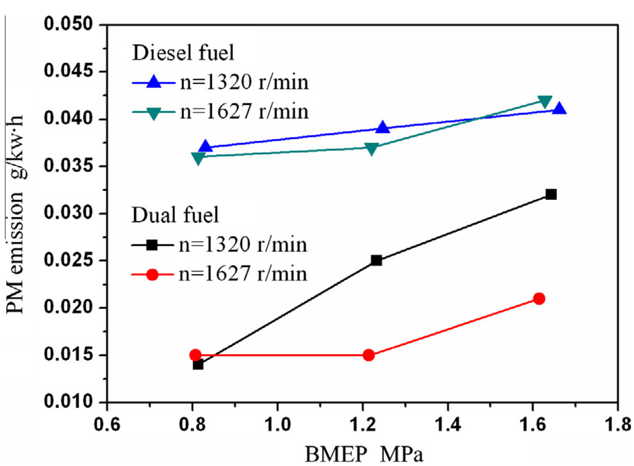

Fig. 7. PM emission characteristics.

during the diffusion combustion process of the pilot diesel fuel in the very fuel rich and high temperature region of the pilot fuel spray core, which is the same with the conventional diesel engines [24]. Some of the soot will be oxidized later when the lean natural gas–air mixture is entrained into the spray core region. However, at high load conditions, with the higher boost pressure and retreated pilot injection timing, the ignition delay time is reduced. So, with the increase of the pilot fuel quantity, more pilot fuel participate in the diffusion combustion process, which result in an obviously increase of the PM emission.

4. Conclusions

For CNG/diesel dual fuel engines, the effects of pilot fuel quantity and injection timing are noticeable and significant. An appropriate understanding of these effects is necessary. The CNG/diesel dual fuel engine emissions have been experimentally investigated in this paper with different pilot fuel quantities and optimized pilot injection timing. The investigation results indicate the following:

(1) The CO emission levels under dual fuel mode are considerably higher than that under normal diesel operation conditions, which are caused by the flame quenching of the lean premixed natural gas–air mixture.
(2) Due to the low combustion temperature of the lean premixed mixture, dual fuel mode averagely reduces NO*x* emissions by 30% in comparison to diesel mode.
(3) The unburned HC emissions of the natural gas fueled dual fuel engines are obviously higher than that of the diesel engines. And around 90% of the THC emissions were unburned methane.
(4) THC emissions reduce significantly with the increase of the pilot diesel quantity.
(5) With the premixed nature of the dual fuel mode and molecular structure of the methane, PM emissions are considerably lower than normal diesel engine. The PM emission is increased with the increase of the pilot fuel quantity.

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