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Combustion process decoupling of a diesel/natural gas dual-fuel engine at low loads

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ABSTRACT

The combustion process of diesel/natural gas dual-fuel engine is complicated. In order to decouple the combustion process of natural gas (NG) and diesel, a wide range of the NG from zero to 75%, by increasing the NG flow rate at a constant air and diesel consumption rate were studied. A detailed analysis based on heat release rate data has been carried out to better understand the effect and underlying mechanism of the two fuel combustion processes. A method of calculating the ratio of heat release from NG combustion to the total heat release through comparing the heat release rate data between dual-fuel mode at different NG quantities and original diesel mode was proposed. The tested engine is a 6-cylinder turbocharged intercooler dual-fuel engine. Several combustion parameters, including in-cylinder pressure, in-cylinder temperature and heat release rate, were analyzed under 1335 rpm, 10% load (A10) condition and 1335 rpm, 25% load (A25) condition. The results show that the heat release rate curves have only one peak firstly, then transform into two peaks, and change into a quasi-single peak at last with the increase of NG quantities under A10 condition when T_{inj} is 7°CA BTDC. The maximum ratio of heat release from combustion by NG around diesel spray to the total heat release is 25.4% and the premixed combustion of diesel occupies the main combustion process, the maximum ratio of heat release from combustion by flame propagation of NG to the total heat release is 75.4% (PES is 73%) and the combustion of NG is the main part of the combustion process. A similar discussion under A25 condition when T_{inj} is 7°CA BTDC and about advancing and retarding T_{inj} under A10 condition was conducted.

1. Introduction

In recent years, tighter emission regulations and the problem of environment and energy are forcing people to look for alternative fuels. NG is widely concerned owing to its abundant resources, high octane number and low price [1]. NG is usually used in CI (compression ignition) and SI (spark ignition) engine as an alternative fuel [2,3]. And the NG HCCI engine is widely developed [4–9]. The mixture of air and NG is difficult to auto-ignition by compression due to its high auto-ignition temperature. Hence, a fuel that can be spontaneously ignited is used to ignite the mixture at the TDC (top dead center) [10,11]. The diesel natural gas dual-fuel engine is one of the main mean to apply NG to the engine. Generally, NG is inducted into the intake port by multi-point injection, and form homogeneous mixture with air, while diesel is directly injected into the cylinder to provide source of ignition around the combustion TDC [12]. The advantages of the engine are able to improve the emission performance of the engine due to NG does not contain aromatic compounds such as benzene and contains less dissolved impurities than petroleum fuels [2]; the disadvantages are low thermal efficiency, high THC emission and decrease power at low load, while knock at high load.

Many researchers discussed the effect of many operating parameter s, including load, speed, engine compression ratio, intake manifold condition, intake configuration, pilot fuel mass inducted, pilot fuel injecting timing, rail pressure, type of gaseous fuel, shape of combustion chamber, in-cylinder bulk flow and methane supply strategy on the combustion process and emission in detail. Papagiannakis and Hountalas [13] compared the combustion process and emissions under both dual-fuel operation and original diesel operation at four different loads of 20%, 40%, 60%, and 80% of full load and three different speeds of 1500, 2000, 2500 rpm through experimental investigation. Selim [14] studied the effect of load on pressure rise rate for dual-fuel and original diesel operation mode when engine speed is 1200 rpm. The results showed that the pressure rise rate increases when the load increases and is always higher than that of original diesel operation. Mansour et al. [15] conducted some experiments to study the effect of speed on specific power and fuel consumption under dual-fuel and diesel operation mode for full load. The results pointed that there is a

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large difference between the power and fuel consumption of the two operating modes at low speed, and no obvious difference at high speed. In addition, Selim [14] investigated that the pressure rise rate decreases as the engine speed increases for dual-fuel and diesel operate mode under medium load. The effect of three pilot diesel mass of 0.15 kg/h, 0.20 kg/h and 0.25 kg/h, on the combustion and emissions of dual-fuel engine has been investigated by Abd et al. [16]. The results showed that with small pilot diesel quantity, the flame cannot propagate throughout the whole chamber owing to the lean mixture, THC and CO emissions increase. The pilot diesel quantity has little effect on flame propagation speed when the mixture concentration is above lean combustion limit. Selim [17] studied the effect of compression ratio on knock onset and ignition failure of a dual-fuel engine. For LPG, NG and methane, reduction compression ratio leads to the occurrence of knock onset later and greatly prolongs the ignition limits. In order to improve emissions, Kusaka [18] installed a heat exchanger in intake system to change the intake temperature and used exhaust gas recirculation (EGR). Intake heating with EGR can improve thermal efficiency, reduce THC and NO_X emissions, but excessive EGR causes the deterioration of combustion process. Donateo [19] investigated the effect of diesel quantity, rail pressure, vertical location of the diesel injector and engine compression ratio on the dual fuel combustion, and three different shapes of combustion chamber were designed and compared by numerical simulation. All the chambers were found to be able to improve the combustion efficiency and reduce the HC emission. Carlucci AP et al. [20–24] studied the effect of in-cylinder bulk flow and methane supply strategies on combustion and emission. Three different bulk flow structures, two different positions of the injector and seven different inlet setups were conducted, and analyzed combustion process based on the in-cylinder luminance.

As we known, the pilot diesel injection timing is a crucial factor that influences the combustion process of dual-fuel engine. Advancing the injection timing, more fuel is burned before TDC and caused the in-cylinder pressure increases and peak pressure moves closer to TDC. Retarding the injection timing, the pilot fuel combustion is delayed and the in-cylinder temperature is not enough to propagate the flame and caused incomplete combustion, which leads to the decrease of cylinder pressure. G.H. Abd Alla et al. [25] examined the effect of advanced injection timing (25°, 27.5°, 30°CA BTDC) on the performance of dual-fuel engine. Advancing the injection timing improve the unburned HC emission and increase thermal efficiency at low load obviously. Wang et al. [26] investigated the impact of pilot diesel ignition mode on combustion and emissions characteristics of a diesel natural gas dual fuel heavy-duty engine. The results show that with normal pilot diesel injection timing, the ignition mode is similar to traditional diesel engine compression ignition (CI) mode, and two-stage autoignition mode can be achieved when advancing diesel injection timing over one fixed value which is determined mainly by mixture temperature. M.C. Cameretti et al. [27] reported that the start of combustion and the speed of flame propagation in mixture are different significantly under two different injection timing (32.5°CA BTDC and 22.7°CA BTDC) by experiment and simulation. A more uniform temperature field is formed in the cylinder when advancing the injection timing, CO and unburned HC are easier to oxidize completely, and consequently, the emissions decrease.

Papagiannakis RG et al. [28,29] examined the effect of natural gas percentage on combustion process and emissions of a dual-fuel engine. The cylinder pressure curve of dual-fuel combustion obviously deviates from the cylinder pressure curve of original diesel combustion and heat release rate curve shows a second peak caused by natural gas combustion with the NG percentage increases. And the results found that the increase of natural gas percentage as the decrease of the air-fuel ratio, and caused lower brake thermal efficiency compared with original diesel operation. With the increase of natural gas percentage, soot emissions significant decrease, the carbon monoxide and unburned hydrocarbon increase.

Table 1
Detailed technical specifications of the test engine.

Engine parameters	Specifications
Bore × stroke	112 × 145 mm
Number of cylinder	6
Displacement	8.6 L
Compression ratio	17.2
Rated power	260 kW at 2100 r/min
Maximum torque	1500 N·m at 1400 r/min
Number of injector nozzle holes	8

In short, the combustion process of dual-fuel was analyzed in depth previously, but there are few research of the combustion process decoupling of diesel and NG. In this paper, in order to decouple the combustion process of NG and diesel, a wide range of the NG percentage energy substitutions, from zero to 75%, by increasing the NG flow rate at a constant air and diesel consumption rate were studied. A detailed analysis based on heat release rate data has been carried out to better understand the effect and underlying mechanism of the two fuel combustion processes.

2. Experimental setup and conditions

2.1. Experimental setup

The test engine used in this study is an 8.6 L, in-line 6-cylinders, 4 strokes, turbocharger, intercooler, heavy-duty diesel/natural gas dual-fuel engine. The detailed technical specifications of the engine are given in Table 1. The fuel properties are listed in Table 2.

A schematic of the engine experimental setup is shown in Fig. 1. The electronically controlled system and NG supply system were designed in the condition of maintaining the universal parts of based diesel engine as many as possible. The multi-point injection NG supply system was designed including development of injector, gas rail and NG filter etc. and appropriate choice of key parts such as regulator and shut-off valve. A dual-fuel electronically controlled system (ECU) was developed with functions such as the diesel injection timing, common rail pressure and pulse control for both diesel and NG, electronic throttle control and communication and so on. Natural gas was charged in the compressed vessels around 20 MPa and decompressed to 0.8 MPa through a regulator warmed by engine cooling water before injected into the intake port.

During the test, the flow rate of diesel was measured by a Toceil CMFD015 mass flow meter, and the flow rate of NG was measured by a Toceil CMF025 mass flow meter, and the flow rate of air was measured by an AVL1000 flow meter. Engine speeds and loads were controlled manually by an eddy current engine dynamometer of 260 kW. The cylinder pressure was measured by a Kistler 6125B piezoelectric transducer and an AVL charge amplifier, which sampled over 200 cycles at intervals of 1°crank angle.

Table 2
Test fuel properties.

Fuel	Diesel	Natural gas
Boiling point(°C)	180–360	− 162
Auto-ignition temperature(°C)	250	650
Octane number	–	130
Cetane number	52.5	–
Stoichiometric air–fuel ratio(kg/kg)	14.3	16.4
Lower heating value(MJ/kg)	43.5	50
Evaporation heat(kJ/kg)	250	–
Volume ratio of rich combustion limits in air (%)	7.6	13.9
Volume ratio of lean combustion limits in air (%)	1.4	5.0