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Experimental and computational study on the effects of injection timing on thermodynamics, combustion and emission characteristics of a natural gas (NG)-diesel dual fuel engine at low speed and low load

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ABSTRACT

In this study, the thermodynamics, combustion and emission characteristics of a NG-diesel dual fuel engine with varying pilot injection degree at low speed and low load were investigated by computational fluid dynamics (CFD) simulation and bench test. Based on tested in-cylinder pressure, the in-cylinder combustion process of NG-diesel dual fuel engine was quantitatively analyzed. On this basis, both the one-dimensional and three-dimensional CFD simulated models were built and then validated by tested data, which were used to analyze the combustion and emission characteristics of NG-diesel dual fuel engine. From this study, the effects of advanced pilot injection degree (APID) on the thermodynamics, combustion and emission characteristics of NG-diesel dual fuel engine were found. With the advancing of pilot injection degree, both the SOC and 50% combustion position are advanced, which leads the maximum in-cylinder pressure and heat release rate (HRR) to increase. The 10–50% combustion duration decreases slightly but the 50–90% combustion duration increases obviously. Meanwhile, both the effective expansion efficiency (EEE) and the percent of heat transfer loss increase, while their increase rates are different, which make the brake thermal efficiency (BTE) firstly increase and then decrease. The BSNOx increases largely while the BSTHC is almost unchanged with the advance of injection timing. Although more HC is generated in the early stage as the pilot injection degree is retarded, the post-combustion becomes clear which accelerates the oxidation of HC. All these have provided theoretical guidance and data support for improving the performance of NG-diesel dual fuel engine.

1. Introduction

In order to reduce baneful emissions and save energy, many countries are actively developing new energy technologies and searching for alternative fuels [1]. Due to the better fuel economy and lower harmful emissions, NG is considered as one of the most promising alternative fuels for internal combustion (IC) engines [2]. With the increasingly stringent emission regulations, various advanced technologies, including exhaust gas recirculation (EGR) [3], turbocharging and variable valve timing (VVT) [4], are applied to NG engines to improve the combustion and emission performance. It is well known that the burning rate of NG is relatively slow, thus the heat-work conversion efficiency and the power performance of NG engine are restricted [5]. Accordingly, there are two major approaches to improve the combustion process of NG engine. One is the NG-hydrogenation and the other is the diesel induced ignition, and both of them are classified as dual fuel engine [6]. The dual fuel combustion mode is regarded as one of the most potential technologies for NG engine, which can improve the fuel economy and reduce exhaust emissions [7]. In a typical NG-diesel dual fuel combustion mode, the NG is inducted in the intake manifold, and then a small quantity of diesel is injected near the top dead center (TDC) to ignite the NG-air mixture [8]. The pilot liquid fuel, which is injected by the conventional diesel injection system, is just used to ignite the mixture and contributes only a small fraction in the engine power output [9,10]. When NG is not available, these dual fuel engines still maintain full diesel capability. Due to the high octane number, NG

Abbreviations: AFR, airfuel ratio; API, after pilot injection; APID, advanced pilot injection degree; ATDC, after top dead center; BMEP, brake mean effective pressure; BTE, brake thermal efficiency; CFD, computational fluid dynamics; CI, compression ignition; CNG, compressed natural gas; DDM, droplet discrete model; DI, direct injection; ECU, electronic control unit; EEE, effective expansion efficiency; EER, effective expansion ratio; EGR, exhaust gas recirculation; EVO, exhaust valve opening; HRR, heat release rate; IC, internal combustion; IVC, intake valve closure; LNG, liquefied natural gas; NG, natural gas; PES, percent energy substitution; PRR, pressure rise rate; RCCI, reactivity controlled compression ignition; RGF, residual gas fraction; SOC, start of combustion; TDC, top dead center; VVT, variable valve timing; WHSC, world harmonized steady-state cycle; WHTC, world harmonized transient cycle

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is more suitable for compression ignition (CI) engines which usually operate with a relatively high compression ratio [11]. Because of the multiple advantages mentioned above, NG-diesel dual fuel combustion mode has received considerable attention from researchers [12].

In recent years, the NG-diesel dual fuel operating mode has been presented in numerous literatures [13]. Papagiannakis et al. [14] investigated the effects of the total air-fuel ratio (AFR) and diesel supplementary ratios on the efficiency and pollutant emissions of a CI engine, and the results are helpful for applying this technology on existing direct injection (DI) diesel engines. Carlucci et al. [15] converted a single-cylinder diesel engine into a dual-fuel engine to operate in different values of engine load and speed and displayed the effect of these parameters on engine performance, in terms of specific emission levels and fuel consumption. Nwafor et al. [16] examined the effect of advanced injection timing on the emission characteristics of dual-fuel engine and the results revealed that CO and CO_2 emissions were reduced through advanced injection timing. Xu et al. [17] studied the effects of pre-injection timing on combustion and emission in a CI NG engine, and indicated that close pre-injection operations lead to the advance of SOC which intensified the combustion of in-cylinder mixture, thereby resulting in higher cylinder pressure, HRR and pressure rise rate (PRR), as well as higher NOx emissions and lower HC and CO emissions. Yang et al. [18] investigated the effects of NG injection time on engine combustion performance and emissions, and claimed that the BTE is increased but the combustion stability slightly deteriorates with retarded NG injection timing. With the development of computer technology, some software have been introduced to research the performance and combustion process of dual fuel engine, like GT-power, AVL-Fire, Converge and so on [19,20]. Kakaee et al. [21] explored the effects of piston bowl geometry on NG-diesel reactivity controlled compression ignition (RCCI) performance and emissions at medium engine load. They found that the bowl profile does not affect the combustion of RCCI engine at low engine speeds, but it has much effect at higher engine speeds, since the chamber geometry has significant influence on squish flow formation, evaporation and mixing processes. Salahi et al. [22] investigated the effect of using a pre-chamber to extend some operating ranges in a RCCI engine by coupled multi-dimensional CFD with detailed chemical kinetic mechanisms, and demonstrated that the proposed strategy could lead to incomplete combustion and formation of related emissions in low loads, due to the jet flame propagation in the main chamber and low fuel equivalence ratio. Jung et al. [23] investigated the effects of intake valve closure (IVC) in dual fuel mode using GT-power, and found that the change in IVC could increase combustion efficiency and affect NOx emissions by controlling the AFR. Wang et al. [24] investigated the effect of the optimized combustion chamber on dual fuel engine by 3-D CFD simulation model coupled with a chemical reaction mechanism, and the results showed that the HC and CO emissions are reduced by 56.47% and 33.55% in the optimized chamber, which is attributed to the higher turbulence kinetic energy. Jafarmadar et al. [25] analyzed the exergy efficiency in a dual fuel engine at four EGR mass fractions (0%, 10%, 20%, and 30%) by a FORTRAN-based code. They found that as the EGR mass fraction increased from 0% to 30% (in 10% increment steps), the exergy efficiency decreased from 48.9% to 28.7%, which is attributed to lower oxygen mass fraction participating in the combustion process.

Although many studies have been carried out on the effects of pilot injection parameters (e.g., pilot injection quantity, timing and pressure) on the performance of NG-diesel dual fuel engine from all aspects, most of them are only based on experimental method. Recently, 3-D CFD simulation method was increasingly used in the research of combustion and emission of IC engine. Nevertheless, the studies on the effect of pilot injection parameters on the combustion of NG-diesel dual fuel engine through 3-D CFD simulation method are still scarce, let alone the coupling analysis with the thermodynamics process of engine. The authors have reviewed lots of literatures, but still failed to find a similar study about the experimental and computational analysis on the effects of injection timing on thermodynamics, combustion and emission characteristics of a NG-diesel dual fuel engine at low speed and low load. Thus, further study is still necessary to exhibit the detailed changing course and three-dimensional distribution of physical quantities for combustion and emission of NG-diesel dual fuel engine. Accordingly, this study aims to analyze the effects of injection timing on thermodynamics, combustion and emission characteristics of a NG-diesel dual fuel engine at low load and low speed through the method of experiment coupling with CFD simulation, which has not only extended this research field, but also contributed to optimize the performance of NG-diesel dual fuel engine.

2. Experiment and CFD simulation

2.1. Engine bench test

The original engine is a six-cylinder, direct injection, turbocharged diesel engine with common rail system, which is manufactured by WEICHAI POWER in China. In order to adjust the dual fuel combustion mode, the fuel supply system and electronic control unit (ECU) of original engine have been simply modified. It is worth mentioning that the compressed natural gas (CNG) was chosen for this study. A summary of the engine's specifications is listed in Table 1.

The diagram of the test platform for the NG-diesel dual fuel engine is shown in Fig. 1 and the specifications of main measuring instruments are given in Table 2. Before the engine bench test, the measuring range and accuracy of test instruments were carefully selected and then accurately calibrated so as to ensure the accuracy and reliability of tested data. More specifically, the cylinder pressure sensor was designed according to the actual working parameters of the engine (e.g., the cylinder pressure range), which was calibrated by the manufacturer and the calibration results were provided to the customer. Based on the standard gases, each measurement module of emission analyzer was calibrated periodically according to the specifications of emission test equipment. Other equipment, e.g., air flowmeter, natural gas flowmeter and diesel flowmeter, were calibrated termly, and the calibration results are within the error range.

The ECU for NG-diesel dual fuel engine has been re-designed by ourselves, which can meet the control demand of both single fuel mode of diesel and dual fuel mode of NG-diesel. In the dual fuel mode, it is possible to control the pulse width of diesel injection, the injection start point, the oil rail pressure and the injection pulse width of CNG, and the engine can be controlled by monitoring the exhaust temperature and cylinder pressure. In this study, the mass of injected diesel fuel was controlled in 7 mg each cycle. NG was injected before the throttle, and the engine operating conditions were adjusted by controlling the throttle opening. As shown in Fig. 1, the CNG system consists of a high pressure NG storage tank, a shutoff valve, a high pressure filter, a NG flow meter, a pressure reducer and a low pressure filter. After the pressure regulator, the NG pressure drops from 18 MPa to 0.8 MPa, and then it is injected into the intake port of engine. The CNG and air blend in the mixer before the throttle valve. In case the CNG is absent, the ECU can switch to the single fuel mode of diesel.

Table 1
Basic parameters of the tested engine.

Item	Content
Displacement (L)	9.726
Bore (mm)	126
Stroke (mm)	130
Original compression ratio	17.0
Connecting rod length (mm)	219
Maximum torque (N·m)/Speed (rpm)	1550/(1200–1500)
Rated power (kW)/Speed (rpm)	247/1900
Number of injector nozzle holes	8
Injector nozzle spray angle (°)	147