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# Effects of natural gas injection timing and split pilot fuel injection strategy on the combustion performance and emissions in a dual-fuel engine fueled with diesel and natural gas

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ABSTRACT

Considering the drawbacks of a diesel/natural gas dual-fuel combustion at low load usually is relative to undesirable natural gas-air-diesel mixture distributions in-cylinder and natural gas supply method and pilot diesel injection strategy are believed to play a critical role in the process of mixture formation in the cylinder. So an experimental study has been conducted to explore the effects of natural gas injection timing and split pilot injection strategy on the combustion performance and emissions characteristics in a diesel/natural gas dual-fuel engine.

In this study, the effects of natural gas injection timing under a constant split pilot injection strategy and a varying first pilot injection timing under an optimized natural gas injection timing on combustion performance and emissions are evaluated. The cylinder pressure, Heat Release Rate (HRR), Pressure Rise Rate (PRR), ignition delay, flame development duration, CA50 and combustion duration as well as THC, CO, $NO_x$ emissions are analyzed for the purpose.

The experimental results indicated that natural gas injection timing and split injection strategy have a significant influence on the combustion performance and emissions characteristics in the dual-fuel engine. The natural gas premixed combustion stage can be enhanced with retarded natural gas injection timing. The pilot diesel combustion stage is weakened under the split injection strategy and the combustion process can be improved by reasonably advanced first pilot injection timing. Moreover, combined variation natural gas injection timing and split pilot injection strategy is a potential way to optimize the performance of the diesel/natural gas dual-fuel engine.

## 1. Introduction

With increasing concerns about the air pollution and the depletion of global oil reserves, in recent years, researchers are trying to find a solution to improve the traditional internal combustion engine in order to realize a more efficiency and cleaner combustion. For this purpose, the Low-Temperature Combustion (LTC) theory had been proposed and is generally regarded as one of the promising theories to guide improving the performance of the traditional diesel engines [1,2]. The dual-fuel operation strategy is a typical method to achieve the LTC in the traditional internal combustion engines and a lot of studies had confirmed that the $NO_x$ and PM emissions in a diesel engine can be simultaneously reduced under the dual-fuel operation strategy [3,4]. As a result, the dual-fuel combustion strategy has caught numerous attentions all over the world and researchers present various concepts of the dual-fuel engines, such as pilot ignited [5,6] and reactivity controlled compression ignition (RCCI) [7,8]. A lot of gaseous fuels were seriously evaluated in the dual-fuel combustion engine this before and natural gas is believed as one of the most suitable alternative fuels applied in the dual-fuel combustion engine due to the wide distribution all over the world, low price compared with conventional fossil fuel and clean burning as well as a good antiknock property [9,10].

In recent years, extensive investigations have been conducted to explore the combustion performance and emissions in diesel/natural gas dual-fuel engines all over the world [11,5]. The effects of various operation parameters on diesel/natural gas dual-fuel engine had been experimental and simulation investigated. For example, the pilot injection timing and pressure [12,13], the substitution rate [14], and natural gas supply method [15] as well as engine operation parameters (speed, load, etc.) [16,17]. Those investigations had confirmed that the diesel/natural gas dual-fuel combustion strategy is one of the most promising methods to realize the high efficiency and low emissions

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**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 |
| RCCI | reactivity controlled compression ignition |
| CO | nitric oxide |
| $NO_x$ | nitrogen oxides |
| THC | total hydrocarbon |
| PRR | pressure raise rate |
| LTC | low temperature combustion |
| PREMIER | premixed mixture ignition in the end gas region |
| CA50 | crank angle at 50% mass fraction burned |
| CNG | compressed natural gas |

combustion in a diesel engine. However, there are still some drawbacks under the dual-fuel combustion mode and need to overcome, such as the unstable combustion performance and higher unburned $CH_4$ emissions under low and medium loads [18].

The previous studies mentioned above indicated that the spatial distributions of natural gas and pilot fuel in cylinder play a critical role in the ignition kernel formation and flame development. Moreover, the thermal and kinetic interaction inside a mixture in cylinder is believed significantly influencing a dual-fuel combustion performance and emissions characteristics. The drawbacks mentioned above are mainly due to inappropriate natural gas-air-diesel mixture distributions in cylinder [15,16]. As a result, some researchers try to improve the mixing process of natural gas and diesel in the cylinder in order to optimize the performance of dual-fuel combustion engines. So the split pilot fuel injection and natural gas port injection strategies have been investigated recently. For example, Yousefi et al. [19,20] developed a multidimensional Computational Fluid Dynamics (CFD) model to explore the different pilot fuel injection strategies in a dual-fuel combustion engine under low load. They compared the effects of single, double and triple pilot fuel injection strategies under the same operating condition. Their studies showed that the pilot fuel injection strategies have a significant influence on the combustion and emissions of a dual-fuel engine. Cagdas Aksu et al. [21] employed the split micro pilot fuel injection strategy to extend the PREMIER (PREmixed Mixture Ignition in the End Gas Region) combustion operation range in a dual-fuel engine and they reported that the PREMIER combustion has been achieved in a wide range under the split pilot fuel injection strategy in an experimental study. Their investigation indicated that the size and rate of growth of flame kernels were obviously influenced by the timing of the second injection. Carlucci AP et al. [15] explore the effects of methane supply method combined with variable in-cylinder charge bulk motion on a diesel/natural gas dual-fuel combustion and emissions. They believed that some stratification of the mixture was obtained by varying the methane supply method combined charge bulk motion. And the stratification will play a positive effect in ignition kernel formation and combustion flame propagation. Yang et al. [22] experimental studied the effect of natural gas injection timing on the combustion performance and emissions in a diesel/natural gas dual-fuel engine. They compared the combustion performance and emissions under the varying natural injection timings under a single pilot fuel injection strategy. The result indicated that a certain degree stratification of natural gas distributions in-cylinder can be obtained by retarding the injection timing and the combustion process have been enhanced.

As can be seen from the above, the spray of pilot fuel and the natural gas distributions in-cylinder have a significant influence on the combustion performance and emissions in a diesel/natural gas dual-fuel engine. The split pilot fuel injection strategy and different natural gas supply method have been studied in order to explore the effects on the combustion process. However, the strategy of combining the split pilot fuel injection and varying natural gas injection timing is rarely studied this before and the combination strategy is believed one of the most promise ways to optimize the ignition kernels formation and flame propagation process in a diesel/natural gas dual-fuel engine [21,11]. So the effects of the combination strategy on the combustion performance and emissions characteristics should be intensively analyzed.

In this study, an experimental study was conducted to explore the effects of split pilot injection and natural gas injection timing on the combustion performance and emissions characteristics in a diesel/natural gas dual-fuel engine. Firstly, the effects of the varying natural gas injection timings under a fixed split pilot fuel injection operation condition were investigated. Then, a set of split pilot fuel injection timings was studied under an optimized natural gas injection timing operation condition. Moreover, the in-cylinder pressures, Heat Release Rate (HRR), PRR, ignition delay, flame development duration, CA50 and combustion duration, as well as regular emissions, have been also carefully analyzed in the paper. Additionally, the comprehensive analysis of combination split pilot fuel injection and natural gas supply method also provide a unique insight to fully understand how to optimize the dual-fuel combustion process and this is also the object of this investigation.

## 2. Experimental apparatus and procedure

### 2.1. Experiment engine and fuels

A diesel engine (G.W.2.8TC) produced by GREAT WALL Co. in China (four cylinders, water cooling, turbocharged, common-rail) have been modified to run in the diesel/natural gas dual-fuel combustion mode. More details of the experimental engine can be found in Table 1. Fig. 1 shows the schematic of the experimental setup. The engine equips an extra multi-point sequential port injection system to control natural gas in dual-fuel operation mode and four natural gas injectors are installed at intake manifold as close as possible to the intake valves for a better dynamic performance of natural gas supply. Compressed Natural Gas (CNG) with 25 MPa is stored in the CNG tank and its pressure is reduced to 0.4 MPa by a two-stage pressure regulator. And then through

**Table 1**
Specifications of the experimental 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 |
| Max. torque | 225 ± 5 N·m (1600–2600 r·min$^{-1}$) |
| Injection system | Bosch CR1P2 |
| Max. injection pressure | 145Mpa |
| 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 |

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