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# Effect of diesel pre-injection timing on combustion and emission characteristics of compression ignited natural gas engine

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ABSTRACT

Pre-injection strategy is considered to be one of the most important ways to improve diesel engine performance, emission and combustion. It is the same important factor in pilot diesel compression ignition natural gas (CING) engine. In this study, effects of pre-injection timing on combustion and emission performances were experimentally studied in a CING engine which was modified from a turbocharged six-cylinder diesel engine. The experiments were conducted at constant speed of 1400 rpm and different engine loads with a constant fuel injection pressure of 1100 bar. Main injection timing was fixed at 10 °CA BTDC in the advance process of pre-injection timing. The cylinder pressure, heart release rate (HRR), pressure rise rate (PRR), start of combustion (SOC) and coefficient of variation ($COV_{IMEP}$), as well as $NO_x$, HC and CO emissions were analyzed. The results indicated that closely pre-injection operations lead to the advance of SOC which intensified combustion of in-cylinder mixture, thereby resulting in higher cylinder pressure, HRR and PRR, as well higher $NO_x$ emissions and lower HC and CO emissions. However, early pre-injection operations lead to lower cylinder pressure, HRR and PRR due to decreasing in combustion intensity. Pre-injection timing of 70 °CA BTDC is a conversion point in which influence of pre-injection fuel on ignition and combustion of natural gas nearly disappeared and lowest $NO_x$ emission could be obtained. Compared with single injection ignition mode, $NO_x$ emissions at the conversion point were reduced by 33%, 38% and 7% at engine load of 38%, 60% and 80% respectively. This is important for the conditions that ignition fuel quantity cannot be further reduced to slow in-cylinder combustion and $NO_x$ emission due to cooling demand of fuel injector. In addition, HC and CO emissions almost maintained in the same level as single injection ignition mode, and even have a certain reduction for some of load conditions, which indicated that early pre-injection timing strategy is effective in reducing $NO_x$ emissions.

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## 1. Introduction

The problems of energy shortage and pollution control with increasingly stringent emission regulation lead to the development of alternative fuels application in internal combustion engines. Natural gas is one of such fuels available in large quantities in many parts of the world at attractive prices. Also, previous studies have shown that natural gas engine have the potential to achieve a large reduction in oxides of nitrogen ($NO_x$) and particulate matter (PM) emissions [1,2], and receives great focus in recent years [3–6].

According to the difference of ignition mode, natural gas engines are mainly divided into spark ignited natural gas (SING) engine and diesel compression ignited natural gas (CING) engine. In SING engine, a single ignition source is provided by spark plug to ignite natural gas. Low ignition energy provided by this SING mode, as well slow flame propagation speed of natural gas combustion results in long combustion duration, also higher thermal load and exhaust temperature. However, in CING engine evaporated pilot diesel fuel can provide a number of ignition sources, which is useful to enhance ignition energy and strengthen natural gas combustion. Such a multipoint ignition mode ensures consistency in the start of combustion in each engine cycle [7]. Also, higher allowable compression ratios are possible with CING engine compared to SI operation, which is an important factor enhancing engine performance. The high compression ratio of most conventional direct injection diesel engine can be maintained when diesel compression ignited natural gas mode is employed. Therefore, pilot diesel compression ignition mode is an important development direction in enhancing power and emission performances of natural gas engine.

In recent years, various investigations have previously been conducted on the combustion and emissions performance of CING engine. Abdelghaffar [8] modified a diesel engine to operate under

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**Nomenclature**

| | | | |
|---|---|---|---|
| AFR | air fuel ratio | HC | hydrocarbons |
| ATDC | after top dead center | HRR | heat release rate |
| ABDC | after bottom dead center | IMEP | indicated mean effective pressure |
| BTDC | before top dead center | IVO | intake valve open |
| BBDC | before bottom dead center | IVC | intake valve close |
| CO | carbon monoxide | NG | natural gas |
| CA | crank angle | $NO_x$ | nitric oxides |
| COV | coefficient of variation | PRR | pressure rise rate |
| CA50 | crank angle for 50% heat release | SING | spark ignition natural gas |
| CING | compression ignition natural gas | SI | spark ignition |
| EGR | exhaust gas recirculation | SOC | start of combustion |
| EVO | exhaust valve open | TDC | top dead center |
| EVC | exhaust valve close | | |

diesel compression ignited natural gas conditions, and showed that diesel CING has lower brake thermal efficiency compared to the diesel mode at part and low load. Gharehghani [9] and Tarabet [10] developed researches on CING mode engine with biodiesel as ignition source, and showed that biodiesel leads to a higher in-cylinder pressure with shorter heat release rate duration, and better combustion stability. Yang [11] explored the influence of the natural gas injection timing under different operation conditions. This study shows that retarded natural gas injection timing under low and part engine loads could enhance flame propagation and improve natural gas combustion efficiency. Also, amount of studies on the potentials of the use of EGR in CING engine are addressed, and the results indicated that EGR is effective in delaying combustion, reducing thermal load and reducing $NO_x$ emission [12,13].

In addition, fuel injection is usually regarded as a critical factor influencing combustion, performance and emission characteristics of diesel engine [14–17]. In CING engine, pilot fuel injection controlling ignition timing of natural gas is the same important factor. Several studies have been conducted to examine the effects of fuel injection parameters such as pilot injection pressure, injection timing and quantity of pilot fuel. Wong [18] reported that exhaust emissions can be reduced with stable combustion in the diesel–natural gas dual fuel system with a micropilot injector. Srinivasan KK [19] discussed the effect of pilot injected quantity and intake charge temperature on the onset of ignition and combustion in a pilot-ignited natural gas engine with early pilot injection strategy. Papagiannakis [20] applied a two-zone phenomenological model to study the effect of the increase of the pilot fuel quantity accompanied with its injection advance by using an existing. Ryu [21] investigated the effect of pilot injection pressure on the characteristics of engine performance and exhaust emissions in a diesel engine using biodiesel–CNG dual fuel. The results show that the indicated mean effective pressure (IMEP) of biodiesel–CNG DFC mode is lower than that of diesel single fuel combustion (SFC) mode at higher injection pressure. But, the increase of pilot injection pressure results in improving in combustion stability of biodiesel–CNG DFC mode. Rimmer [22] investigated the effect of the single-pilot-injection timing and quantity on the dual-fuel engine performance and emissions in a high-speed engine. The results identify the limits of single-injection timing during dual-fuel combustion and the gains in the engine performance and stability that can be achieved through optimizing pilot injection timing. Yang [23] investigated the effects of natural gas injection timing on the combustion and emissions performance under different pilot injection pressure and timing at low load conditions and suggested that higher pilot injection pressure and advanced pilot injection timing obtained better BTE and emissions except for $NO_x$. Li [24] studied effects of diesel injection parameters combined with equivalence ratio and EGR on combustion process, HC emissions and the thermal efficiency at low loads, and in the paper three typical combustion modes including h, m and n are analyzed. Wang [25] developed a study on the effect of pilot diesel injection timing in diesel/natural gas dual fuel engines. The study finds that a two-stage autoignition mode can be achieved when advancing diesel injection timing over one fixed value which is determined mainly by mixture temperature, and in the two-stage autoignition mode, the brake thermal efficiency and THC emissions almost keep unchanged, but $NO_x$ emission decreases largely.

Despite of the many studies made on effect of pilot injection parameters (eg: pilot injection quantity, timing and pressure), there is still a lack of basic information concerning pre-injection of pilot ignition diesel, which is a two-stage diesel injection strategy including pre-injection and main injection. This study aims to offer new information to understand characteristics of CING engine at pre-injection strategy. A turbocharged 6-cylinder diesel engine with high pressure common-rail system was modified to operate in diesel CING mode. Experimental study was conducted to evaluate the effect of pre-injection timing on combustion and emission characteristics of CING engine. Moreover, cylinder pressures, heat release rate (HRR), start of combustion (SOC), combustion phase (CA50) and cycle-to-cycle variation of IMEP ($COV_{IMEP}$) also were analyzed in this work. This provides basis for the optimization of pilot pre-injection strategy in CING engine.

## 2. Experimental setup and procedure

A six-cylinder, direct injection, turbocharged, common rail diesel engine was modified to operate in diesel CING mode. The specifications of the original engine are listed in Table 1.

The schematic diagram of CING engine and natural gas fueling system are shown in Fig. 1. The engine was equipped with common rail direct injection system, with advanced features for controlling start of injection timing. The maximum fuel injection pressure could be varied up to 180 MPa and this system was capable of multiple injections (2 pre-injections in addition to the main injection). New CING mode ECU was developed to control fuel injection and natural gas injection. Exhaust gas analyzer was equipped to measure the emissions of $NO_x$, HC and CO. Also, fuel conditioning system, lubricating oil conditioning system and coolant condition system equipped with for experimental investigations in controlled conditions. The accuracy and uncertainty of measurements were shown in Table 2.

Effects of pre-injection timing on combustion, performance and emissions were investigated at different engine loads and constant

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