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Pre-injection strategy for pilot diesel compression ignition natural gas engine

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HIGHLIGHTS

- Early pre-injection modes provide better NO_x emission.
- Effects of fuel pre-injection parameters are studied for early pre-injection modes.
- Increase of pre-injection quantity ratio leads to slower combustion and lower NO_x.
- Increase of fuel injection pressure leads to increase of burning rate and higher NO_x.

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ABSTRACT

For pilot fuel compression ignition natural gas (CING) engine, pre-injection strategy of pilot fuel is an important ways to improve engine performance, emissions and combustion. In this study, effects of pre-injection parameters on combustion and emissions performance were experimentally studied in a pilot diesel CING engine which was modified from a turbocharged six-cylinder diesel engine. The cylinder pressure, heart release rate (HRR), start of combustion (SOC), duration of combustion (DOC) and coefficient of variation (COV_{IMEP}), as well as NO_x and HC emissions were analyzed. The results indicate that early pre-injection mode leads to lower cylinder pressure and HRR due to decrease of combustion intensity, and thereby lower NO_x emission is obtained. In contrast, closely pre-injection timing leads to largely strengthening in combustion which is not beneficial for improving NO_x emission performance.

Furthermore, effects of pre-injection quantity ratio and fuel injection pressure on combustion and emissions of early pre-injection operation modes (on pre-injection timing of 70°CA BTDC) were analyzed. Increase of pre-injection quantity ratio leads to decreasing in ignition intensity which delayed SOC and slowed burning rate of in-cylinder mixture, and thereby leads to lower cylinder pressure and HRR. Due to slowing in in-cylinder combustion, combustion temperature decreased, and hence leads to lower NO_x emission and higher HC emission. However, too high pre-injection quantity ratio leads to unstable ignition and even unstable combustion which is not beneficial for engine performance. Increasing fuel injection pressure leads to larger fraction of premixed quantity of injected fuel which increased ignition energy and leads to rapid combustion, and hence higher cylinder pressure and HRR were obtained. Due to the increase of burning rate of in-cylinder mixture, in-cylinder combustion temperature was increased, and hence leads to higher NO_x emission and lower HC emission.

1. Introduction

Due to energy shortage and pollution control with increasingly stringent emission regulation, more and more alternative fuels are developed to apply in internal combustion engines. Natural gas (NG) 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 better exhaust emissions performance than gasoline and diesel engine [1,2], and receives great focus in recent years [3–7].

Pilot diesel compression ignited natural gas (CING) engine is an important direction for the utilization of natural gas in internal combustion engine [8–11]. In CING engine, pilot diesel was injected into combustion chamber at near top dead center as an ignition source to ignite in-cylinder NG/air mixture. This kind of ignition mode provides a number of ignition sources, which are useful in optimizing natural gas combustion and improving

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Nomenclature

ATDC	after top dead center
ABDC	after bottom dead center
BTDC	before top dead center
BBDC	before bottom dead center
CO	carbon monoxide
CA	crank angle
COV	coefficient of variation
CING	compression ignition natural gas
CNG	compressed natural gas
DOC	duration of combustion
EVO	exhaust valve open
EVC	exhaust valve close
HC	hydrocarbons
HRR	heat release rate
IMEP	indicated mean effective pressure
IVO	intake valve open
IVC	intake valve close
NG	natural gas
NO_x	nitric oxides
SOC	start of combustion
TDC	top dead center

emissions. Yao [12] revealed the ignition mechanism of the diesel pilot natural gas by the experimental study in an optical engine. They found that ignition location of diesel and natural gas was more dispersed and closer to cylinder wall. Papagiannakis [13] investigated effect of natural gas mass ratio on the combustion and the emission characteristics. The results indicated that ignition delay and combustion duration were generally prolonged with the increase of natural gas mass ratio, and NO_x and particulate matter (PM) emissions were reduced. In addition, such a multipoint ignition mode ensures consistency in the start of combustion in each engine cycle [14], and high compression ratio of most conventional direct injection diesel engine can be also maintained when this kind of ignition mode is employed.

Usually, fuel injection is a critical factor influencing combustion, performance and emission characteristics of diesel or dual fuel engine [15–17]. In CING engine, pilot fuel injection controlling ignition timing of natural gas is the same important factor. Also, various investigations have previously been conducted to study effects of fuel injection parameters such as pilot injection pressure, injection timing and quantity of pilot fuel on the combustion and emissions performance of CING engine. Wong [18] reported miropilot ignition fuel injection is beneficial for reducing exhaust emission of diesel and NG dual fuel system at stable combustion condition. Rimmer [19] 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. Liu [20] further conducted study on effect of pilot fuel quantity on emissions under an optimized pilot injection timing in a CNG/diesel dual fuel engine and concluded that decrease of pilot fuel quantity leads to lower combustion temperature, and hence results in lower NO_x emission and higher HC emission. Srinivasan [21] studied early pilot injection strategy in a pilot-ignited natural gas engine and discussed effect of pilot injected quantity and intake charge temperature on the onset of ignition and combustion. Ryu [22,23] concluded that the increase of pilot injection pressure results in lower smoke, but higher NO_x emission from the experimental study in a single cylinder diesel engine with biodiesel as ignition source. The results also show that increasing in fuel injection pressure leads to higher burning rate which is useful for improving combustion stability. Yang [24] 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. Paykani [9] developed simulation study on the combustion and emission performance of natural gas/diesel reactivity controlled compression ignition combustion with split fuel injection strategy, and the results show that better emission performances are achieved in this kind of RCCI combustion. Cameretti [25] conducted a numerical and experimental study on effect of the diesel oil injection timing on the performance and emissions of a dual fuel compression ignition engine. The experimental results put into evidence a strict sensitivity of the engine response to the start of the injection, which confirms that proper strategies should be determined for optimizing the dual-fuel operation in terms of both energetic and environmental behavior. Li [26] experimentally studied effects of fuel injection parameters on combustion and emissions at different equivalence ratio and EGR condition and analyzed three typical combustion modes of h, m and n. Wang [27] 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, there is still a lack of study concerning pre-injection strategy of pilot fuel in CING engine. In the application of fuel compression ignition natural gas engine, usually, a certain quantity fuel supplement is necessary to satisfy cooling demand of fuel injector. But the increase of ignition fuel supplement leads to more ignition energy and hence higher combustion intensity which is not beneficial for reducing NO_x emission. So, pre-injection strategy under constant total fuel injection quantity was developed in this study so that NO_x emission could be decreased, simultaneously satisfying cooling demand of injector. Also, effects of pre-injection parameters on combustion and emission characteristics of CING engine were investigated to offer further information for the application of pre-injection strategy. A turbocharged 6-cylinder diesel engine with high pressure common-rail system was modified to operate in pilot diesel CING mode. Experimental study was conducted to evaluate the effect of pre-injection parameters (including pre-injection timing, pre-injection quantity ratio and fuel injection pressure) on combustion and emission characteristics of CING engine. Moreover, cylinder pressures, heat release rate (HRR), start of combustion (SOC), duration of combustion (DOC) and cycle-to-cycle variation of IMEP (COV_{IMEP}) also were analyzed in this work. This provides basis for the optimization of pre-injection strategy of pilot fuel 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.