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Experimental investigation on performance and heat release analysis of a pilot ignited direct injection natural gas engine

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Pilot ignited direct injection natural gas engines undertake significant advantages over conventional diesel engine with specific combustion mode. In this paper, extensive experiments have been carried out to provide further understanding of performance and heat release rate under different operating conditions. Through the experimental investigations and detailed analysis, it is demonstrated that shortened injection interval and diesel injection pulse width as well as increased injection pressure lead to an increase in maximum in-cylinder pressure and deteriorated combustion noise. The maximum heat release rate is raised by retarding injection timing, reducing injection interval, shortening diesel injection pulse width and increasing injection pressure. The stability of combustion shows uncertain trends with the variation of injection timing and pilot diesel injection quantity, while can be generally improved by the adoption of shorter injection interval and lower injection pressure. It is also revealed that fuel economy can benefit from the application of advanced injection timing, smaller diesel injection pulse width, shorter injection interval and higher injection pressure.

1. Introduction

Nowadays, the increasing concerns on environmental crisis and energy shortage have led to a research focus on the application of alternative fuels for transportation applications, especially for heavy-duty ones [1]. Natural gas, with the advantage of low carbon content, is widely recognized as having great potential to solve the problem of greenhouse gas emissions [2]. Further, rapid global expansion of unconventional natural gas development, such as shale gas and coal seam gas, has made it a more desirable fuel [3]. However, in most current spark ignition natural gas engines, natural gas is premixed with air and a throttle is utilized to control the air-fuel ratio, hence reduction in thermal efficiency and associated sacrifice of output torque in order to avoid damages caused by knocking are inevitable [4,5]. Pilot ignited direct injection natural gas engines use the technique of injecting small amount of diesel to ignite the directly injected natural gas. As the fuels are non-premixed, higher thermal efficiency could be obtained with little changes to the baseline diesel engine [6]. In addition, pilot ignited direct injection natural gas engines, by using the diesel thermodynamic cycle, can maintain operating temperature similar to diesel engines, thus eliminating the thermal load problems and leading to improved durability.

The combustion process of pilot ignited direct injection natural gas engines is fairly different from both spark ignition natural gas engines and diesel engines, as the combustion is compression initiated and two fuels are involved. Additionally, both fuels are injected directly by the same injector at the end of compression stroke, therefore the working behavior of pilot ignited direct injection natural gas engines is also distinguished from conventional dual fuel engines and low pressure direct injection natural gas engines, in which spark plug or glow plug is employed to act as ignition source. Much work has been done on the performance and combustion characteristics in this type of engine. Douville [7] developed a multi-zone combustion analysis model to investigate the combustion rates

Abbreviations: ATDC, after top dead center; BTDC, before top dead center; BSFC, brake specific fuel consumption; CA, crank angle; C.H.R, cumulative heat release; CNG, compressed natural gas; COV, coefficient of variation; D2P, second derivation of in-cylinder pressure; DPW, injection pulse width of pilot diesel; DRP, diesel rail pressure; ECU, electronic control unit; EGR, exhaust gas recirculation; GPW, injection pulse width of natural gas; H.R.R, heat release rate; IMEP, indicated mean effective pressure; LNG, liquefied natural gas; MFB0–10%, 0–10% mass fraction burned duration; MFB10–90%, 10–90% mass fraction burned duration; MFB50%, phase angle of 50% mass fraction burned; PSEP, pilot diesel to natural gas injection separation; rpm, revolutions per minute; n, engine speed; NSOI, start of natural gas injection.

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along with heat transfer to cylinder walls and evaluated the effects of injection timing, injection rate, engine load and speed using both experimental and computational methods. It can be summarized from his study that the combustion rate of dual fuel mode was higher than that of pure diesel mode and the combustion rates of both modes decreased with increasing load as a result of the increased proportion of mixing-controlled combustion. Hill and Douville [8] proposed a method incorporating nonlinear regression technique to determine the cylinder heat loss rate, the ignition delay, the mass burning rate as well as the burned gas temperature by measurements of intake/exhaust charge and in-cylinder pressure curves. Li et al. [9] presented a CFD (computational fluid dynamics) combustion model together with an injector model to simulate the in-cylinder mixing and combustion process. They also calibrated and validated the model by a set of experimental results. It was revealed by their simulation results that the model could simulate accurately under conditions without EGR (exhaust gas recirculation), however, under high EGR conditions, the model had large prediction errors. Lee et al. [10] modeled the combustion of both fuels based on different detailed chemical mechanisms to find a mechanism that could adequately predict the combustion process with reasonable computational efficiency. On the basis of the modeling work, they concluded that the changing trends of the simulation results were not sensitive to the mechanism applied. McTaggart-Cowan et al. assessed the effects of injection pressure, injection interval [11,12], fuel composition [13] as well as compression ratio [14] on the combustion behavior. Their experimental results suggested that the whole combustion duration of both fuels were shortened at higher injection pressures and the combustion events of diesel and natural gas were difficult to differentiate at shorter injection intervals. They also found that ignition delay and maximum heat release rate could be reduced by adding nitrogen, hydrogen, ethane and propane to natural gas and the combustion duration was prolonged with the addition of hydrogen, ethane and propane. Besides, the peak cylinder pressure was reduced and the maximum heat release rate was increased resulting from the reduction of compression ratio. Wager and Wallace [15] conducted a series of experiments to make comparisons between the mixing rates and combustion characteristics of natural gas jets issuing from elliptical and round nozzle designs. They stated that the overall combustion process, including ignition delay and combustion duration, exhibited little differences between the two nozzle designs, though the peak value of heat release rate and the combustion efficiency were higher with the employment of round nozzles. They also adopted the optical devices to make combustion image analysis. The image histograms indicated that more intense flames and an earlier peak of luminosity could be observed by using elliptical nozzles. Munshi et al. [16] incorporated both experimental and computational methods to analyze the effect of partially-premixed combustion strategy on the engine performance and emission characteristics. Their experimental results indicated that the optimum engine performance could be obtained with the utilization of different combustion strategies under different loads and their CFD modeling results demonstrated that the level of turbulence was a key factor for flame propagation, which was highly dependent on the mixing condition in the combustion chamber. Cheenkachorn et al. [17] compared the performance and emission characteristics of the dual fuel operation with that of the diesel operation. According to their findings, the thermal efficiency and volumetric efficiency of dual fuel operation were lower than single diesel operation while the specific fuel consumption was slightly improved. What's more, the effects of injector structure were systematically tested by Laforet [18] with three different injectors, including the baseline one; it was found that the new injectors could achieve better fuel economy under most operating conditions.

In the present study, heat release rate, cyclic variation along with BSFC (brake specific fuel consumption) were analyzed to make a further understanding of the combustion characteristics and evaluate the effects of four important injection parameters on the performance of a pilot ignited direct injection natural gas engine. Systematic experiments were carried out at a constant engine speed of 1200 rpm with engine torques of 1300 N m and 1700 N m, as these are the most commonly used operating conditions for heavy-duty engines. As mentioned above, most previous studies focused on heat release analysis of this type of engine are based on numerical simulation, very limited researches have been done on the thoroughly exploration of the general performance of this kind of engine, particularly the combustion cyclic variation.

2. Experimental apparatus and test conditions

2.1. Experimental apparatus

The baseline engine for the experiments was a turbocharged, intercooled 6-cylinder diesel engine. The specifications of the engine are listed in Table 1. The engine was modified by incorporating a fuel supply system with integrated pressure regulating module for adjusting the injection pressure of both fuels and refitting the engine head in order to equip with concentric needle injectors, in which the injection timing was controlled by two solenoids separately. The engine was coupled to an eddy current dynamometer (Xiangyi GW630) and instrumented with piezoelectric transducers (Kistler 6067C) flush mounted to the bottom of cylinder head to measure the in-cylinder pressure at a resolution of 0.5 °CA (crank angle). A coriolis mass flowmeter (Emerson CNG050) and a diesel consumption meter (AVL 733S) were also equipped for natural gas mass and diesel flow measurements. As shown in the schematic diagram of the test bed in Fig. 1, natural gas was supplied to the gas rail after pressurized by the pump and regulated to the appropriate pressure by the integrated pressure regulating module, where the pressure of diesel was also adjusted to a value a little higher than that of natural gas after pressurized by the diesel pump. Intake air mass flow rate measurements were made before the compressor with a laminar flowmeter (ToCeiL-LFE400). The pressure and temperature of the intake charge were measured by an intake pressure sensor (Kistler 4007B) and an intake temperature sensor (Delphi 25036751), both of which were located in the intake manifold. It should be noted that before the measurements (including in-cylinder pressure of 100 consecutive cycles) of every single test condition, the engine was stabilized for at least five minutes.

2.2. Test conditions

The purpose of this work is to examine systematically the effects of various injection parameters on the performance and combustion characteristics of pilot ignited direct injection natural gas engine. The effect of every parameter was identified by

Table 1
Engine specifications.

Item	Specification
Number of cylinder	6
Engine type	Turbocharged, water cooled
Combustion chamber	bowl
Bore × stroke/mm	126 × 155
Displacement/L	11.6
Compression ratio	17
Rated power/kW	353
Rated speed/r·min^{-1}	2100
Idle speed/r·min^{-1}	600

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