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Impact of pilot diesel ignition mode on combustion and emissions characteristics of a diesel/natural gas dual fuel heavy-duty engine

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HIGHLIGHTS

- Combustion performance of a dual fuel heavy-duty engine was examined.
- Diesel injection timing was controlled over a wide range at a light load operation.
- Two-stage autoignition mode was observed with advancing injection timing.
- Diesel ignition mode has an obvious effect on the following combustion quality.
- Higher thermal efficiency and lower emissions can be achieved simultaneously.

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ABSTRACT

The brake thermal efficiency and exhaust emission issues are still not fully-resolved to diesel/natural gas dual fuel engines. To better understand the effect of pilot diesel ignition mode on combustion and emissions characteristics of dual fuel engines, a detailed study concerned with diesel injection timing was conducted. The testing work was operated on a 6-cylinder turbocharged intercooler diesel/natural gas dual fuel heavy-duty engine at light load operations, and diesel injection timing was controlled over a very wide range. The investigated results show that the diesel injection timing (T_{inj}) has an obvious effect on pilot diesel ignition mode. A significant advancing T_{inj} leads to pilot diesel ignition mode differs from traditional diesel engine compression ignition mode in the sense that it does not occur at a specific place in the spray, which is a two-stage autoignition mode. With advancing T_{inj}, engine combustion and emissions characteristics, including cylinder pressure, cylinder temperature, heat release rate, start of combustion (SOC), ignition delay, combustion duration, crank angle of 50% heat release (CA50), nitrogen oxides (NOx) and total hydrocarbon (THC), show completely different variation trends in different ignition modes. Overall, higher thermal efficiency and lower emissions can be achieved simultaneously in two-stage autoignition mode. Satisfactory results can be obtained with higher brake thermal efficiency (35%), lower NOx (60 ppm) and THC (0.4%) emissions, when T_{inj} is 42.5 °CA BTDC.

1. Introduction

As known, thermal efficiency and emission performance of internal combustion engine are still hot issues for all of research institutes and engine researchers around the world, and never stop. In return, more and more valuable research achievements emerge in an endless stream [1–3].

In term of alternative fuel, natural gas has recently emerging as a promising automotive alternative fuel because of its rich reserves and clean emissions. After long-term unremitting efforts of research, many proven techniques have been widely used [4–7]. Despite all this, a lot of further study is still in progress, one of which is about advanced diesel/natural gas combustion process and control techniques.

The development of advanced techniques of diesel engine, gasoline engine and natural gas engine brings many novel ideas to dual fuel engine [8–10]. In recent decades, the control technology of diesel engine made great progress, especially engine electronic control technology and high pressure common rail diesel fuel injection technology, which promoted the progresses of diesel/natural gas dual fuel engine combustion process and control techniques [11–13]. The latest researches show that Controlled Auto-Ignition (CAI) and

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Nomenclature

BMEP	brake mean effective pressure	NOx	nitrogen oxides
BTDC	before top dead center	SOC	start of combustion
CA	crank angle	THC	total hydrocarbon
CA50	crank angle of 50% heat release	T_{inj}	the pilot diesel injection timing
CI	compression ignition	λ	the air excess ratio
CNG	compressed natural gas	η_e	the brake thermal efficiency
HCCI	Homogeneous Charge Compression Ignition		

Homogeneous Charge Compression Ignition (HCCI) combustion are radically different from the conventional spark ignition (SI) combustion in a gasoline engine and compression ignition (CI) diffusion combustion in a diesel engine. The combination of a diluted and premixed fuel and air mixture with multiple ignition sites throughout the combustion chamber eliminates the high combustion temperature zones and prevents the production of soot particles, hence producing ultra-low NOx and particulate emissions. Therefore, CAI/HCCI combustion represents for the first time a combustion technology that can simultaneously reduce both NOx and particulate emissions from a diesel engine and has the capability of achieving simultaneous reduction in fuel consumption and NOx emissions from a gasoline engine [14].

Although HCCI combustion in natural gas engines has been explored for many years, there are still some fundamental issues that remain to be resolved [15–19]. Facing the same problem as gasoline engine, it is difficult to control auto-ignition timing and combustion duration because they are controlled primarily by the chemical kinetics of fuel-air mixture, which is crucial to engine operating limit. In addition, the problem of the homogeneous mixture natural gas engine is the relatively larger cycle-by-cycle variations especially under lean combustion condition and large EGR condition [20–22]. The diesel spray ignited diesel/natural gas dual fuel engine can greatly decrease the cycle-by-cycle variations, which is a merit of operating natural gas. Amongst the numerous research papers on diesel/natural gas engine performance published over the last decade, most of them focus on the effect of boundary condition, but few concentrate on pilot diesel ignition mode e.g. CI mode and HCCI mode [23–27].

It is well known that diesel ignition process is crucial to diesel/-natural gas engine combustion process. As mentioned above, there are two kinds of diesel ignition mode. If a perfectly homogeneous mixture is created, the pressure and temperature rise during the compression stroke will lead to spontaneous ignition which differs from the classical diesel autoignition in the sense that it does not occur at a specific place in the spray, but simultaneously across the combustion chamber. Consequently, if autoignition occurs simultaneously in the whole cylinder, no high temperature flame front will appear as in the case of spark ignition engines. The absence of a high temperature flame front will lead to a practically negligible formation of nitrogen oxides, and due to the homogenized lean mixture, fuel rich zones are absent and therefore soot formation is also avoided. Reactions in HCCI engines generally involve a two-stage process, including both the so-called low temperature and high temperature reactions [28]. For diesel/natural gas dual fuel engine, two-stage process is different from those of diesel-like or gasoline-like fuel HCCI combustion and still unclear up to now. During the low temperature reactions, it may be more like that of diesel HCCI combustion for its pilot diesel ignition. But, during the high temperature reactions, the conclusion cannot be determined now for their different physical and chemical properties. It is worthwhile spending some time on researching the differences.

In addition, mixture composition, in-cylinder temperature and pressure have a dominant effect on ignition process of pilot diesel. If no other engine setting is modified, autoignition takes place at a given crank angle position independently of the start of injection, provided that enough time is made available to create a more or less homogeneous mixture [29]. But, too early injection certainly will lead to diesel impingement and poor atomization quality for lower in-cylinder temperature. On the contrary, too late injection will lead to traditional compression ignition [30]. At the same time, the effects of pilot diesel fuel ignition mode on the following mixture combustion need further investigation. So, further detailed investigation about impact of diesel injection timing should be carried out. To better understand the effect of pilot diesel ignition mode on combustion and emissions characteristics of dual fuel engines, a detailed study concerned with diesel injection timing was conducted. The testing work was operated on a 6-cylinder turbocharged intercooler diesel/natural gas dual fuel heavy-duty engine at light load operation, and diesel injection timing was controlled over a very wide range.

2. Experiment

2.1. Experimental setup

The research engine used for this study is an 8.6 L, 6-cylinder, turbocharged, intercooler, heavy-duty and diesel/natural gas dual fuel engine. The technical specifications of the engine were given in Table 1.

A schematic of the engine experimental setup is shown in Fig. 1. A dual fuel electronic-controlled system was developed with functions such as direct diesel injection, multi-point natural gas injection, electronic throttle control, idle flashover, fault diagnosis and communication. Natural gas was charged in the compressed vessels around 20 MPa and decompressed to 0.8 MPa through a regulator warmed by engine cooling water before injected into the intake port. The diesel and natural gas injection timing, pressure and pulse width were controlled with computer. In this research, pilot diesel was injected into cylinder during compression stroke with a common rail fuel injection system with different injection timing, and compressed natural gas (CNG) was injected into the intake port at a constant crank angle. Natural gas was selected as

Table 1
Detailed technical specifications of the test engine.

Engine parameters	Specifications
Bore × stroke	112 × 145 mm
Number of cylinders	6
Displacement	8.6 L
Rated power/speed	260 kW@2100 r/min
Compression ratio	17.2:1
Number of injector nozzle holes	8