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Full Length Article

Experimental investigation on the effects of nozzle-hole number on combustion and emission characteristics of ethanol/diesel dual-fuel engine

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ABSTRACT

Since fuel reactivity stratification greatly influences the combustion process of dual-fuel engines and nozzle geometry directly affects the distribution of direct injected fuel, experiments were carried out to investigate the effects of nozzle-hole number on the combustion and emissions of dual-fuel engine. The experiments were performed on a single-cylinder diesel engine with port injection of ethanol and direct injection of diesel. There are four diesel injectors with 4, 5, 6 and 8 nozzle holes studied in this paper, while the total orifice areas and included spray angles of the injectors are kept the same. With reduced nozzle holes, the experimental results showed that both the in-cylinder peak pressure and PPRR (peak pressure rise rate) of ethanol/diesel dual-fuel combustion were decreased while with extended combustion durations. This is mainly because the number of high fuel reactivity regions was reduced with fewer diesel sprays, then the combustion of premixed ethanol was slowed down which consequently decreased the heat release rate. With reduced nozzle holes, the engine-out NOx emissions were decreased, and soot emissions were slightly increased while still maintained at quite low level. The UHC and CO emissions were slightly increased with reduced nozzle holes which resulted in lower combustion efficiency. However, the influences of nozzle-hole number on dual-fuel combustion were gradually decreased with advanced injection, which was mainly because of the enhanced diesel/air mixing. The experimental results indicated that dual-fuel combustion with reduced nozzle holes could achieve moderate heat release with lower PPRR.

1. Introduction

Diesel engines have been widely used for various applications in modern society due to the advantage of high fuel efficiency. However, soot and NOx emissions have been a challenge for diesel engines because of the heterogeneous nature of conventional diesel combustion [1]. In order to further reduce diesel engine emissions to meet the stringent emission regulations in the future, researchers have put forward the concept of Premixed Compression Ignition Low Temperature Combustion (PCI-LTC) [2,3]. It has been proved that these combustion strategies could simultaneously reduce soot and NOx emissions while maintaining equivalent thermal efficiency with traditional diesel engines [4,5]. However, for most single-fuel PCI strategies, the ignition timing is no longer coupled with fuel injection since ignition is often retarded until the end of injection. Furthermore, the highly premixed fuel/air mixture often results in rapid pressure rise once after ignition [6]. Although exhaust gas recirculation (EGR) is a useful technique to control PCI combustion process, the increasing demand of EGR ratio limits the engine loads. Additionally, PCI with external EGR is generally unstable during transient operation because of the delay in EGR delivery timing [7]. To meet these challenges, researchers have proposed the concept of dual-fuel PCI combustion, such as Reactivity Controlled Compression Ignition (RCCI) [8], Homogeneous Charge Induced Ignition (HCII) [9], dual-fuel Highly Premixed Charge Combustion (HPCC) [10], dual-fuel compound Homogeneous Charge Compression Ignition [11], etc. The dual-fuel PCI combustion has been proved a very promising combustion strategy to meet the strict emission regulations in the future [8–14]. Previous studies have shown that RCCI combustion could achieve over 50% indicated thermal efficiency under the test conditions, while both engine-out soot and NOx meet American EPA HD 2010 emission regulations without after-treatment [13,14]. Meanwhile, compared with single-fuel PCI strategy, dual-fuel PCI could provide better control of combustion phasing and heat release rate by adjusting direct injection strategy and port fuel proportion [15–17].

The dual-fuel PCI combustion is often performed with port injection of a lower reactivity fuel combined with direct injection of a higher reactivity fuel, and the direct in-cylinder blending of two fuels leads to stratification in equivalence ratio as well as fuel reactivity [8].

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Meanwhile, the fuel reactivity stratification of in-cylinder charge is the main difference compared with single-fuel PCI strategy, and this feature of the in-cylinder charge consequently leads to different combustion process. Jiang [18] investigated the combustion characteristics of gasoline/diesel HCII strategy based on an optical engine, and the results showed that multi-ignition was first observed and then the small ignition pockets gradually proceeded around due to flame propagation. Kokjohn [19] investigated the effects of temperature and fuel stratification on RCCI combustion using optical diagnostics and chemical kinetics modeling. The results show that the ignition location and growth rate of reaction zone are mainly determined by fuel reactivity stratification. Additionally, to improve the performance of dual-fuel engines, the main factors influencing the combustion and emission characteristics of dual-fuel strategy have been extensively investigated in previous studies, including fuel reactivity [15,20], port fuel proportion [9,21], as well as direct injection strategy [12,17,22] and piston bowl geometry [23,24]. Splitter [15] compared E85/diesel and gasoline/diesel RCCI combustion, the results showed that E85/diesel RCCI combustion could achieve higher engine load while with lower EGR demand, which is mainly due to the larger fuel reactivity gradient of in-cylinder charge. Meanwhile, increased port fuel proportion as well as lower fuel reactivity of port fuel could reduce the global fuel reactivity, which consequently resulted in prolonged ignition delay and retarded combustion phasing. Therefore, E85/diesel dual-fuel operation needs higher diesel content to maintain the combustion phasing due to the lower fuel reactivity of E85. Hanson [22] investigated the effects of direct injection strategy on dual-fuel combustion, including the injection timings and proportions of first and second injections. The results showed that retarded injection and higher diesel amount in the second injection could increase the fuel stratification, which consequently resulted in advanced combustion phasing as well as increased PPRR (peak pressure rise rate). It is also found that double injections can provide a 40% reduction in CO and UHC (unburned hydrocarbon) emissions, which is mainly because the more distributed diesel increased the fuel reactivity of bowl and squish regions [17]. Moreover, NOx emissions could also be reduced with multiple direct injections under high load condition, which is mainly because multi-injection enhanced diesel/air mixing. Dempsey [23] found that the wide shallow piston bowl could yield 2% to 4% absolute improvement in gross thermal efficiency of RCCI operation, which is mainly due to the lower heat transfer loss.

Dec found that the heat release rate of HCCI (Homogeneous Charge Compression Ignition) combustion could be controlled using equivalence ratio stratification of gasoline [25]. Meanwhile, previous studies have confirmed that compared with equivalence ratio stratification, fuel reactivity stratification plays an important role in controlling heat release rate [26]. There are many factors influencing the fuel reactivity stratification in dual-fuel combustion, such as the fuel reactivity of port injected fuel and direct injected fuel, port fuel proportion and direct injection strategy. For instance, ethanol and gasoline are often employed as the port injected fuel due to the lower fuel reactivity. Moreover, it's well known that ethanol (RON ~ 107) presents lower fuel reactivity than gasoline (RON commonly below 98), thus ethanol/diesel dual-fuel combustion could produce larger gradient in fuel reactivity than that of gasoline/diesel, and previous studies imply that larger fuel reactivity gradient is beneficial to extending the combustion duration [15,27]. Kokjohn [28] studied the effects of fuel reactivity stratification produced by different direct injection timings on the combustion process of dual-fuel operations based on an optical engine. The experimental results showed that early direct injection led to nearly homogeneous mixture and consequently resulted in weak gradient in fuel reactivity, while retarded direct injection near TDC led to over-stratified charge due to the insufficient fuel/air mixing. However, both over and weak fuel reactivity stratification of in-cylinder charge led to rapid heat release, while moderate stratification in fuel reactivity with appropriate fuel injection timing resulted in relatively mild combustion. Therefore, the in-cylinder fuel stratification is the key to control dual-fuel combustion process.

In dual-fuel combustion, as the lower reactivity fuel delivered by port injection is almost uniformly mixed before direct injection, the fuel stratification is mainly determined by the distribution of higher reactivity fuel. In addition to the injection strategy, the nozzle geometry of the direct injector can also affect fuel distribution, including the number of nozzle holes, orifice diameter and included spray angle [29,30]. However, studies about the influences of the direct injector geometry on the combustion of dual-fuel engines are relatively rare in previous research. Yaliwal [31] investigated the effects of injectors with different numbers of nozzle holes on diesel/HOME (Honge methyl ester)-producer gas (mainly methane, hydrogen and carbon monoxide) dual-fuel combustion. However, only the results of effective thermal efficiency and main emissions were illustrated in this study, and the influences of injector geometry on fuel stratification and combustion process of dual-fuel operation were not discussed.

In this study, experiments were conducted to investigate the influences of nozzle-hole numbers on combustion and emissions of ethanol/diesel dual-fuel operation. Since port fuel proportions and direct injection timings are the main factors influencing the fuel reactivity stratification in dual-fuel combustion, the effects of different injectors coupled with various port fuel proportions and direct injection timings are studied in the experiments.

2. Experimental setup

Fig. 1 shows the schematic of the engine layout. A single-cylinder, naturally aspirated diesel engine equipped with a high pressure common rail injection system was used to perform the experiments in this study. The main specifications of the diesel engine are given in Table 1. For dual-fuel combustion in this study, ethanol was delivered with port injection during the intake stroke and diesel was directly injected into the cylinder. Table 2 shows the main fuel properties of ethanol and diesel used in this study. It can be seen that ethanol presents much higher RON than diesel fuel, and also the RON of ethanol is higher than gasoline (RON commonly below 98). For all the test conditions, the injection pressure of port fuel was 3 bar with injection timing maintained at −330 °CA ATDC, and the direct injection pressure of diesel was 60 MPa. Table 3 gives the specifications of different direct injectors employed in the experiments. In this paper, four nozzles with different orifice numbers were investigated, while the total orifice areas and included spray angle of the injectors were maintained the same. For all the employed nozzles, the orifices are all evenly distributed around the central axis of the injector. It should be noted that the original injector of the diesel engine has the same geometry parameters as the 8-orifice nozzle employed in this study. The experimental results showed that when the injection pressure was kept constant, the injection durations for same amount of diesel were very close for different nozzles. As for the electronically controlled common rail injection system of practical diesel engines, the actual fuel injection commonly slightly lags behind the drive current. The lag time is mainly determined by mechanical structure of the injector, including the response characteristics of solenoid valve and nozzle needle. During the experiments of this study, only the nozzle part of the injector was changed each time, thus the lag time of actual injection could be maintained the same for different nozzle cases.

The in-cylinder pressure was acquired with Kistler 6125C cylinder pressure transducer coupled with Kistler 5018 charge amplifier. The top dead center (TDC) was measured by an optical encoder. For each test condition, in-cylinder pressure traces of 200 consecutive cycles at steady state operations were acquired. The COV (coefficient of variation) of IMEP (indicated mean effective pressure) was used to assess the stability of the dual-fuel engine operation in this study. The COV of IMEP is essentially the variability of engine load and is defined as the ratio of the STD (standard deviations) of IMEP over the averaged value of IMEP. The ignition delay is defined as the duration from start of