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Research Paper

Modulated diesel fuel injection strategy for efficient-clean utilization of low-grade biogas

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HIGHLIGHTS

- Influences of direct injection strategy on biogas RCCI mode are researched.
- Excessive early pilot injection timing leads to the retard of combustion.
- Overall indicated thermal efficiency of low-grade biogas can be higher than 40%.
- Pilot injection timing has strong influence on particle size distribution.
- Composition of biogas has a great influence on the gas emissions.

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ABSTRACT

Recently, as a kind of renewable fuel, low-grade biogas has been researched to apply in internal combustion engine. In this paper, an experimental study was conducted to study the influence of injection strategies on the efficient utilization of low-grade biogas in Reactivity Controlled Compression Ignition (RCCI) mode with port fuel injection of biogas and in-cylinder direct injection of diesel based on a modified electronic controlled high-pressure directly injected compression ignition engine. Considered the high proportion of inert gas in biogas, a four-components simulated gas (H_2:CO:CH_4:N_2 = 5:40:5:50 vol%) has been selected as test fuels to simulate biogas. The effects of several injection control parameters such as pilot injection timing, main injection timing, common rail pressure and pilot injection ratio on the combustion and emissions are analyzed in detail. The research demonstrates that the main injection timing can effectively control the combustion phase and excessive early pilot injection timing leads to retard of combustion. CO emissions are relatively high due to homogenous charge of biogas. NOx and smoke emissions can be effectively controlled. In RCCI mode, the indicated thermal efficiency of biogas/diesel can reach 40%.

1. Introduction

Due to the global huge pressure on energy issues and environmental pollutions, the clean and efficient combustion of biomass-based fuels has been a research hotspot in the field of internal combustion engine in recent years [1–3]. Biofuels can relieve the severe dependence of energy on the fossil energy. Meanwhile, it can reduce the carbon emissions in the whole life cycle of fuels [4,5]. Studies show that the physicochemical properties of biomass fuels have great influence on engine performance and emissions [6,7]. Recently, biogas has received wide attention due to the advantages of wide raw material sources and relatively lower preparation costs [8–11].

As a kind of high octane number fuel, biogas can be effective utilized in the spark ignition (SI) engine [12–14]. Some researches show that the inert gas in biogas is conducive to reducing NOx emissions [15]. But the high proportion of inert gas in biogas results in the decrease of heat value and flame propagation velocity of biogas which partly leads to the combustion instability [16]. The mixing of hydrogen into biogas can effectively enhance the combustion [17]. Meanwhile, the increase of H2 content could accelerate combustion and extend operation range of low temperature combustion significantly [18,19].

In order to realize the efficient utilization of biogas, the application of biogas in the compression ignition engine under different combustion modes has also been researched [20–22]. Considering the inherent defects of HCCI model on ignition control [23,24], biogas-diesel dual fuel compression ignition combustion is more attractive and has been widely studied [22,25,26]. Barik [27] found

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that the volumetric efficiency reduced gradually with the port injected biogas increasing. Cacua et al. [28] studied the operation and performance of a diesel-biogas dual fuel engine and found that the increase of intake oxygen concentration helped to enhance the combustion stability, shorten the ignition delay, improve the combustion rate and reduce the CH4 emissions.

Recently, the research team in university of Wisconsin-Madison proposed reactivity controlled compression ignition mode (RCCI) based on the dual-fuel combustion, which has been studied widely [29–33]. Through studying the influence of common rail pressure on RCCI combustion, Walker et al. [34] found that the higher the direct common rail pressure in cylinder, the easier the control of the combustion phase. Splitter et al. [35] found that the highest thermal efficiency of RCCI combustion could reach 60% with optimum combustion control strategy and thermodynamic conditions. Qian et al. [36,37] conducted the RCCI combustion experiment in a single-cylinder engine fueled with ethanol, butanol, n-amyl alcohol and n-heptane. They found that properties of port injected fuel have strong effects on combustion process and emissions. Zhu et al. [38] studied direct injection timing of RCCI and found that optimizing the injection timing accommodated to properties of port injected fuel and alternative rate has great impacts on the efficient utilization of fuel.

In RCCI mode, two kinds of fuels with opposite combustion characteristics were injected into the cylinder through two independent injection systems. Namely, low reactivity fuel (such as gasoline and ethanol) was injected by port injection and high reactivity fuel (diesel, dimethyl ether, n-heptane, etc.) was directly injected into the cylinder [39–41]. The optimal combustion phase can be obtained via using different reactivity fuels, which can reduce engine emissions, improve thermal efficiency. For reasons above and for the efficient utilization of low-grade biogas in RCCI mode, the effects of injection strategy on the combustion and emissions of biogas RCCI in a single-cylinder common rail diesel engine was studied in this paper. Combined with two-stage injection strategy, the effects of injection parameters on the combustion and emissions of biogas/diesel in RCCI was comprehensively studied by varying main and pilot injection timing, pilot injection ratio and common rail pressure, etc.

2. Experimental setup

2.1. Experiment equipment and procedure

The specifications of the dual fuel engine and experiment procedure have been introduced in our previous work [42]. This paper focuses on the influence of injection strategy on the combustion characteristics and emissions of biogas-diesel RCCI combustion. In this experiment, the overall lower heating value per-cycle was maintained at about 2.0 kJ/cycle and the energy share of biogas was fixed at about 60%. The EGR rate was controlled at about 50%.

2.2. Test fuels

The direct injected fuel was commercial diesel while the port injected fuel was biogas. Considering larger proportion of inert component in biogas, a four-components syngas (H_2:CO:CH_4:N_2 = 5:40:5:50 vol%) was selected as test fuels to simulate biogas. More details of biogas can be observed in Table 1.

2.3. Definition of the combustion parameters

The basic parameters of the experiment have also been defined including CA10, CA50 and CA90 in our previous work [43]. Besides, EGR rate is calculated by CO_2 concentration in the intake gas and the concentration of CO_2 and CO in the exhaust gas [44,45]:

Table 1
Components and properties of biogas.

Components and properties	Units
H_2 (vol%)	5
CO (vol%)	40
CH_4 (vol%)	5
N_2 (vol%)	Rest
Lower heat value (MJ/kg)	6.33
Molecular weight (g/mol)	26.1
Density (kg/m^3) (101 KPa, 25 °C)	1.063

$$\mathrm{EGR}(\%) = \frac{con_{CO_{2in}} + \mathrm{con}_{CO_{2air}}}{con_{CO_{2ex}} + con_{CO_{ex}}} \times 100\%$$

In the formula: $con_{CO_{2in}}$ is the volume fraction of CO_2 imported into the intake manifold. $\mathrm{con}_{CO_{2air}}$ is the volume fraction of CO_2 in the air. $con_{CO_{2ex}}$ is the volume fraction in the exhaust, and $con_{CO_{ex}}$ is the volume fraction of CO in the exhaust.

The pilot injection ratio (PIR) is defined as the ratio of the pilot injected diesel quantity m_{SOI1} to the total injected diesel quantity. And the pilot injection ratio can be worked out by the formula:

$$\mathrm{PIR} = \frac{m_{SOI1}}{m_{SOI1} + m_{SOI2}} \times 100\%$$

In the formula: m_{SOI1} refers to the mass of the pilot injected diesel, while m_{SOI2} refers to the mass of the main injected diesel.

3. Results and discussion

3.1. Effects of injection timing on the combustion and emissions

To research the effects of injection timing on biogas/diesel RCCI combustion mode, in this section, the pilot injection ratio was kept at 60% and the common rail pressure was kept at 120 MPa. Fig. 1 shows the effects of direct injection timing on the in-cylinder pressure and heat release rate. In Fig. 1(a), it can be seen that with the advance of main injection timing, the peak values of the in-cylinder pressure and heat release rate curves increase and the heat release phase becomes earlier, which indicates that main injection timing has effective control on the combustion phase of RCCI with biogas/diesel as fuels. The increase of the peak values of the heat release rate curves is mainly due to the advance of main injection timing, which enables more fuels to be burned before top dead center (TDC) and contributes to the higher temperature accumulated in cylinder during the compression stroke.

From Fig. 1(b), it can be seen that with the advance of pilot injection timing, the heat release phase is delayed and the peak values of heat release rate curves increase firstly and then decrease. The pilot injection is mainly for improving the reactivity of the homogenous premixed biogas. As pilot injection timing advances, the pilot injected diesel diffuses more in the direction of cylinder wall and then the atomization area of main injected diesel is more difficult to form the combustible region, which results in the delay of combustion phase. Besides, the diffusion of pilot injection can improve the reactivity of biogas but also increase the occurrence of wall-wetted phenomenon, which leads to the decrease of gross in-cylinder reactivity. The interaction of the two factors contributes to the wave of the peak values of heat release rate curves.

For the further study on the effects of direct injection timing on biogas/diesel RCCI mode, the effects of injection timing on the ignition delay and combustion duration are presented in Fig. 2. As shown in Fig. 2, the ignition delay increases with the advance of