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Cyclical variations of a HCCI engine fueled with n-butanol

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The 2nd cylinder of a water-cooled, naturally aspirated double-cylinders diesel engine was modified to operate on HCCI combustion mode. By changing intake temperature, mixture concentration and engine speed, the effects of parameter variation on cyclical variations of an HCCI engine fueled with n-butanol were investigated in this study. The results show that the peak cylinder pressure (P_{max}) rises as the intake temperature or engine speed increases while reduces as the excess air ratio (λ) increases. The coefficient of variations for P_{max} (COV_{Pmax}) is minimized at high intake temperature, low λ or high engine speed, which are 1.32%, 1.53% and 1.45%, respectively. Therefore, the optimal parameters may be obtained to improve the combustion stability of HCCI engines.

Keywords: HCCI, n-butanol, intake temperature, excess air ratio, cyclical variations

INTRODUCTION

Homogeneous charge compression ignition (HCCI) combustion is a new combustion mode, which compresses the premixed homogeneous air-fuel mixture until its automatic ignition near top dead center (TDC). This combustion mode combines the advantages of compression ignition engine and spark ignition engine [1]. In HCCI engines, the each point of premixed air-fuel mixture in combustion chamber is ignited simultaneously and the heat is released rapidly, close to the ideal constant volume combustion [2]. These contribute to the high thermal efficiency. Moreover, the HCCI engine may run with the lean homogeneous air-fuel mixture. This results in the low-temperature combustion, which subsequently produces low NOx and less soot due to the temperature of combustion area in HCCI engine lower than compression ignition engines and spark ignition engines.

However, the combustion process of HCCI engines is instability because of misfire and knock so as to cause the HCCI engine operate within a relatively small range of speed and load. The combustion stability of HCCI engine is mainly controlled by chemical kinetics and influenced by various parameters [3]. The experimental research of the cyclical variations of HCCI engine conducted by Mauya et al under a fixed speed showed that the coefficient of variations (COV) increase as the intake temperature rises and the λ decreases [4]. Li et al conducted an experimental study on a single cylinder diesel engine to investigate the effects of parameters such as compression ratio and inject pressure on cyclical variations of HCCI engine. They found that the cyclical variation is significantly influenced by ignition timing and retarded the ignition timing can lead to an increase of cyclical variations [5]. Xue et al investigated the cyclical variations of HCCI engine by changing the parameters such as intake temperature and mixture concentration and point out that the optimal intake temperature and mixture concentration may be obtained to ensure the combustion stability of HCCI engines [6].

As a potential renewable alternative fuel, the energy density and cetane number of n-butanol are higher than alcohol fuel (such as methanol and ethanol), which can meet the performance requirement of compression ignition engine [7]. Furthermore, the n-butanol is oxygenated fuel and has high latent heat of vaporization, which may reduce the cylinder temperature and improve the NOx and soot emission of diesel engines. Therefore, an experiment on the influence of the various parameters such as intake temperature, mixture concentration and engine speed on the cyclical variations of HCCI engine fueled with n-butanol is investigated in this study. The aim of this research is to explore the cyclical variations of HCCI engine and provide the basis for the intake temperature, mixture concentration and engine speed optimization in an HCCI engine.

EXPERIMENTAL SETUP

Experimental apparatus

To evaluate the cyclical variation of HCCI engine, a modified double-cylinder, four-stroke, water-cooled, naturally aspirated and direct-injection engine is used in this study. The

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engine specifications are given in Table 1. Engine loads and speeds are controlled by an eddy current engine dynamometer (CW25, Cama, Luoyang, China) of 25 kW.

To operate the test engine on HCCI combustion mode, a few modifications are made for the test engine. Fig.1 shows the schematic diagram of experimental apparatus used in this study. Among them, the 1st cylinder is kept on its original combustion mode, but the 2nd cylinder is converted into HCCI combustion mode. The control system of intake temperature, installed in the 2nd cylinder, is used to control the 2nd cylinder intake temperature.

And the corresponding concentration homogeneous mixture is provided to the cylinder by PFI fuel injection system. The in-cylinder pressure is measured by a piezo-electric type pressure sensor (6052A, Kistler) installed on the 2nd cylinder and is amplified by a charge amplifier (5019, Kistler). The pressure data are taken over 150 cycles and acquired by a combustion analyzer (Kibox 283A, Kistler). The COV_{Pmax} is calculated based on the cylinder pressure.

Table 1. Specifications of test engine.

Model	CT2100Q
Combustion chamber shape	ω
Cylinder	100×105
Displacement(L)	1,65
Compression ratio	17:1
Intake valve opening angle	17°CA
Intake valve closing angle	43°CA
Exhaust valve opening angle	47°CA
Exhaust valve closing angle	17°CA

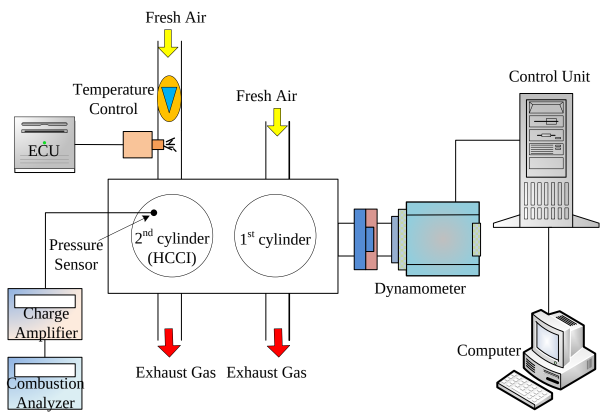

Fig.1 Schematic diagram of experimental apparatus.

Experimental procedure

Before the start of experiment, the 1st cylinder is started with diesel firstly, which drives the test one for warm-up until the coolant and lubricating oil temperature reached about 80˚C. Then, the engine is adjusted to the test conditions: to stop diesel fuel to the 1st cylinder, meanwhile start the 2nd one for HCCI combustion and record cylinder pressure data. The steady state tests are repeated at least twice to ensure that the results are repeatable within the experimental uncertainties.

Data processing

The cyclical variations are the parameters which may characterize the combustion stability of each cycle [6]. The combustion stability, fuel economy and emission can improve by reducing the cyclical variations of cylinder pressure. This paper uses the coefficient of variations for P_{max} (COV_{Pmax}) to evaluate the cyclical variations of HCCI combustion. And its calculation formula is

$$COV_{P_{max}} = \frac{\delta_{P_{max}}}{\bar{P}_{max}} \times 100\% \qquad (1)$$

Where, $\delta_{P_{max}}$ is the standard deviation of P_{max}, and $\bar{P}_{max}$ is the average value of P_{max} in 60 continuous cycles.

RESULTS AND DISCUSSION

Effect of intake temperature on COV_{Pmax}

Fig. 2 shows the COV_{Pmax} of HCCI engine fueled with n-butanol under different intake temperature at engine speed of 1000 r/min and λ of 2.5, respectively. It is shown that the peak cylinder pressure increases while the COV_{Pmax} decreases as the intake temperature rises. This is reasonable because the rise of intake temperature leads to increase the temperature of compression process, raise the activation energy of fuel mixture, and intensify the molecular motion of fuel mixture. These contribute to the more effective collision between fuel mixtures molecular, which subsequently enhance the combustion intensity and increase the quantity of heat release. Meantime, high intake temperature may promote the breaking of chemical bond and produce massive free radical, which can promote the chain reaction and accelerate the combustion rate, reduce the combustion duration and make the distribution of peak cylinder pressure centralized.

Effect of mixture concentration on COV_{Pmax}

Fig. 3 shows the COV_{Pmax} of HCCI engine fueled with n-butanol under different mixture concentration at engine speed of 1000 r/min and intake temperature of 140℃, respectively. The mixture concentration is expressed by excess air ratio λ, shown in the figure, and the mixture becomes lean with the increase of λ. It is observed that the peak cylinder pressure increases and

COV_{Pmax} decreases as the λ reduces. It is considered that the ignite temperature is significantly influenced by mixture concentration. As the λ reduces, the fuel in per unit air-fuel mixture increases and the ignite temperature reduces; in this case, the air-fuel mixture is ignited more easily, leading to a stronger combustion and more heat release. Moreover, the mixture concentration is a key parameter to affect the formation of free radical. The rate of free radical production increases under the condition of lower λ, which may intensify the chemical reaction rate, enhance combustion intensity, reduce combustion duration and reduce the COV_{Pmax}.

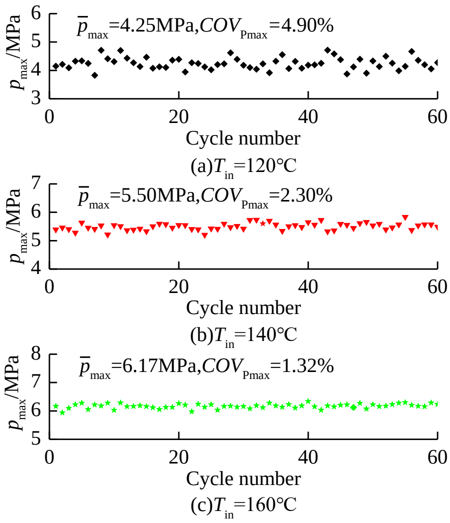

Fig. 2. The COV_{Pmax} of HCCI engine for various intake temperature.

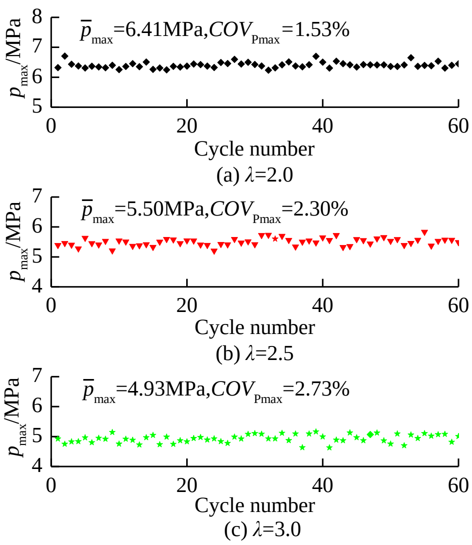

Fig. 3. The COV_{Pmax} of HCCI engine for various λ

Effect of engine speed on COV_{Pmax}

Fig. 4 shows the COV_{Pmax} of HCCI engine fueled with n-butanol under different engine speed at intake temperature of 140˚C and λ of 2.5, respectively. It is found that the peak cylinder pressure increases as COV_{Pmax} decreases with the increase of engine speed. The in-cylinder air motion is strengthened as engine speed increases.

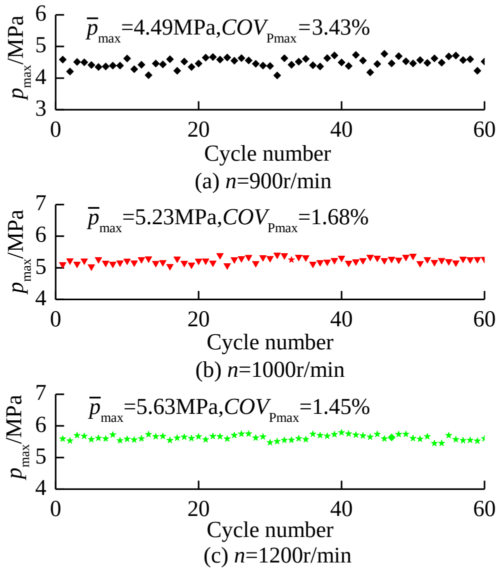

Fig. 4. The COV_{Pmax} of HCCI engine for various engine speeds

Consequently, it causes the air-fuel mixture more homogeneous, the effective collision between fuel molecules more frequently. Moreover, it is also possible that the heat loss reduces and thermal load rises as the engine speed increases, which may improve the temperature of air-fuel mixture and promote the formation of free radical. All these lead to promote auto-ignition, intensify combustion and increase the quantity of heat release. In addition, the strength of in-cylinder air motion and increase of air-fuel temperature are contribute to increase the heat release and improve the combustion condition so as to make the distribution of peak cylinder pressure centralized and improve the combustion stability.

CONCLUSIONS

(1) The P_{max} increases as the intake temperature rises. The COV_{Pmax} is minimized at the intake temperature of 140˚C, and this temperature is the optimal.

(2) The higher P_{max} and lower COV_{Pmax} may be obtained at rich mixture, and this means that the combustion stability may be improved by the rich mixture.

(3) The P_{max} increases as the engine speed rises. Under the condition of higher engine speed, the lower COV_{Pmax} may be obtained at relatively lower intake temperature.

(4) The higher engine speed and richer mixture accomplish with relatively higher intake temperature may be a potential tool to improve the

cyclical variations of HCCI engines.

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