Analysis of Two-Stage Heat Release in HCCI Combustion with Dimethyl Ether

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ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) combustion with dimethyl ether has been carried out in a single cylinder engine with a transparent piston. The engine was operated at 800 rpm with a wide-open throttle. The intake-premixed mixture was preheated with an electric heater to promote auto-ignition. HCCI combustion with dimethyl ether indicates multi-stage heat releases. The influences of equivalence ratio and intake temperature on the characteristics of auto-ignition in the HCCI engine were investigated. In order to understand reaction mechanism of auto-ignition and combustion mechanism in HCCI engine, spectrum analysis of chemiluminescence was carried out.

Keywords: Homogeneous Charge Compression Ignition, Dimethyl Ether, Multi-Stage Heat Release, Spectrum Analysis of Chemiluminescence

INTRODUCTION

Although HCCI [1, 2] engines are expected to have both higher thermal efficiency and lower nitrogen oxide (NO_x) emissions, they have problems with high hydrocarbon (HC) and carbon monoxide (CO) production, high rates of heat release, and difficulty in controlling auto-ignition. HCCI has no flame propagation; instead, the whole mixture burns almost homogeneously during combustion. The combustion process in HCCI engines is due to auto-ignition of an unburned mixture. HCCI combustion of most fuels displays a peculiar two-stage heat release. The first peak of heat release is the heat released during the first stage of ignition, which is described by low-temperature chemical kinetics. The main ignition stage follows the first stage. At lower temperatures, degenerative chain-branching processes control ignition. In order to control the two-stage auto-ignition in an HCCI engine, the reaction mechanism of auto-ignition must be understood.

Dimethyl ether (DME, CH_3OCH_3) [3] is a promising alternative fuel that is suitable for compression ignition engines. DME engines have the potential to solve the air pollution problems caused by soot and NO_x, due to the oxygen content of DME and the absence of carbon-carbon bonds. DME can be produced from hydrocarbons via a relatively cheap one-step synthesis. DME has a high cetane number of 55-60, and is therefore suitable for HCCI engines. Moreover, DME shows very strong low-temperature kinetic reactions in HCCI. A study of HCCI fueled with DME may provide useful information on the low-temperature kinetic reactions in HCCI operation of other fuels. The oxidation of DME has been examined at room temperature and atmospheric pressure in a number of laboratory studies [4]. Recent research has led to the development of a detailed chemical kinetics model of DME combustion [5, 6].

This study investigated the auto-ignition characteristics of an HCCI engine fueled with dimethyl ether (DME), using a single cylinder engine with a transparent piston. The influences of equivalence ratio and intake temperature on the characteristics of auto-ignition were investigated. Spectrum analyses of chemiluminescence were used to investigate the two-stage heat release.

EXPERIMENTAL APPARATUS AND PROCEDURE

HCCI fueled with DME was studied in an optical access engine, which was a modified 4-stroke spark-ignition engine with a single-cylinder and a compression ratio of 9.0. Figure 1 shows a schematic diagram of the experimental apparatus. The inlet airflow rate was measured with a laminar flow meter. The fuel flow rate was measured with a second laminar flow meter, and adjusted with a needle valve. Fuel was supplied to the intake pipe via a small tube just before an electric heater. To initiate HCCI combustion, a higher inlet temperature is necessary. Therefore, the inlet air was preheated with an electric heater to achieve auto-ignition around TDC. The mixture in the cylinder was assumed to be homogeneous. During experiments, the cylinder pressure was recorded at every 0.5 CAD to obtain the instantaneous heat release.

The engine provided optical access via an extended piston and a quartz window. In order to acquire the light emitted naturally during the HCCI combustion process, naturally emitted light was measured using a spectrometer equipped with an intensified CCD. Light emanating from the flame or reaction zone was collected by an optical fiber and transferred to the spectrometer slit. By gating the intensifier synchronously with the engine, we were able to collect light at specific crank angles.

EXPERIMENTAL RESULTS

Effects of intake temperature and equivalence ratio

HCCI combustion is influenced by the intake mixture temperature, T_{in}, and equivalence ratio, ϕ, due to auto-ignition of the premixed mixture. The effects of intake temperature and equivalence ratio on ROHR were investigated.

Figure 2 shows the in-cylinder pressure history, in-cylinder temperature, and the ROHR for equivalence ratios of 0.31, 0.33, and 0.35. The mixture temperature was estimated using the in-cylinder pressure. The onsets of the first peak in the ROHR were located at the same crank-angles. As the equivalence ratio increased, the height of the second peak in the ROHR increased and the onset of ROHR was advanced. Figure 3 shows the relationship between the in-cylinder temperature and the ROHR. The onset of the first peak in the ROHR was located at an in-cylinder temperature of 750 K. The onset angle of the second peak in the ROHR was located at 950 K. As the equivalence ratio increased from 0.29 to 0.35, the onsets of the first and second peaks in the ROHR were at the same in-cylinder temperature. In the range of equivalence ratios considered, a low temperature reaction appeared at an in-cylinder temperature of 750 K. The appearance of low and high temperature reactions was largely dependent on the temperature of the pre-mixture. As the equivalence ratio increased from 0.29 to 0.35, the shape of the second and third peaks of ROHR changed dramatically. As the equivalence ratio increased, the peak value of the ROHR increased and the ROHR showed multi-peak heat release. The influence of equivalence ratio on the high temperature reaction was very large.

Figure 4 summarizes the effects of intake mixture temperature and equivalence ratio on heat release during HCCI combustion. A lower intake temperature and equivalence ratio caused the first peak in the ROHR to be larger than the second. In this case, the heat release was very small. As the intake temperature and equivalence ratio increased, the maximum value of the second peak in the ROHR and the heat release both increased. When the intake temperature exceeded 350 K and the equivalence ratio was richer than 0.34, advance ignition caused a knock phenomena. We concluded that the various shapes of multi-stage heat release resulted from the various intake temperatures and equivalence ratios.

Spectrum analysis of chemiluminescence

As the HCCI combustion process is dependent mainly on chemical reactions, it is not easy to control the auto-ignition process under the condition of several loads and engine rotating speed. One of the best ways to understand the auto-ignition process in HCCI combustion is spectrum analysis of chemiluminescence. Therefore, chemiluminescence analyses were conducted using a spectrometer equipped with an intensified CCD. By synchronizing the gating of the intensifier with the engine, we were able to collect light at specific crank angles. The experimental conditions were selected for different shapes of the ROHR with changing equivalence ratios.

a: The first peak in the ROHR is larger than the second.

b: The first peak in the ROHR is smaller than the second.

Figure 5 shows the crank-angle-resolved light spectra of chemiluminescence in HCCI combustion. In case a, specific light spectra were observed at crank angles from 3 to 23 degrees. These spectra indicate broadband emissions at wavelengths from 300 to 550 nm. In case b, strong emissions were observed near a crank angle of 7 degrees before TDC. These spectra show the same broadband emissions at wavelengths of 300 to 550 nm. The emission intensity was greater in condition b than in condition a. This luminescence is attributed to CO-O recombination [7, 8], which occurs in the region of final oxidation due to higher in-cylinder temperature. After a crank angle of 5 degrees before TDC, strong infrared emissions were observed at 720 and 770 nm, which are attributed to H_2O and CO_2 heat radiation [7]. Figure 6 shows the relationship between the CO-O recombination spectra and the ROHR. There is good agreement between the crank angles at which the peaks of CO-O recombination and the ROHR occurred. We concluded that CO-O recombination with final oxidation occurred at a crank angle of about 7 degrees before TDC, and then H_2O and CO_2 appeared.

CONCLUSIONS

Investigations of the auto-ignition characteristics of HCCI engine fueled with DME were performed using a single cylinder engine with a transparent piston. The results obtained in this work are summarized as follows:

(1) The influences of equivalence ratio and intake temperature on characteristics of auto-ignition in the HCCI engine were investigated. With the increase of intake temperature and equivalence ratio, various heat release was observed. The three-stage heat release was also observed.

(2) Spectrum analyses of chemiluminescence using spectroscopy were carried out in order to investigate the two-stage heat release. During main heat release, CO-O recombination continuous spectrum was strong. A strong correlation between rate of heat release and CO-O recombination spectrum was found.

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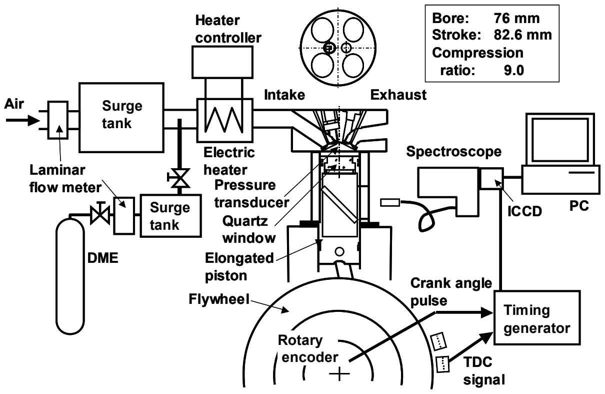

Fig. 1 The schematic diagram of experimental apparatus

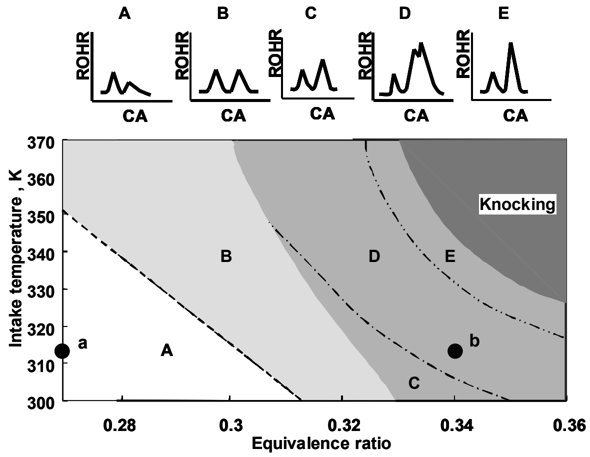

Fig. 4 Effects of equivalence ratio and intake temperature on rate of heat release

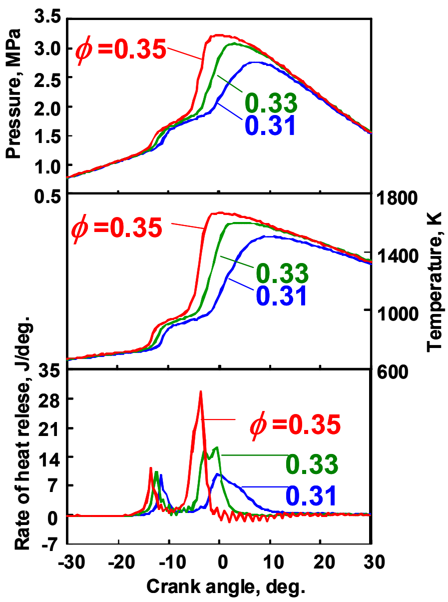

Fig. 2 Effect of equivalence ratio on HCCI combustion

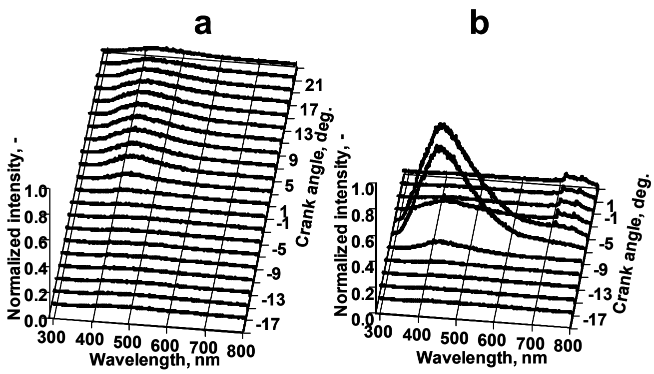

Fig. 5 Crank angle resolved spectrum of chemiluminescence

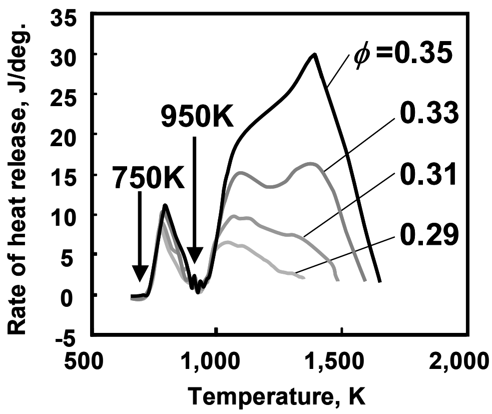

Fig. 3 In-cylinder temperature vs. rate of heat release

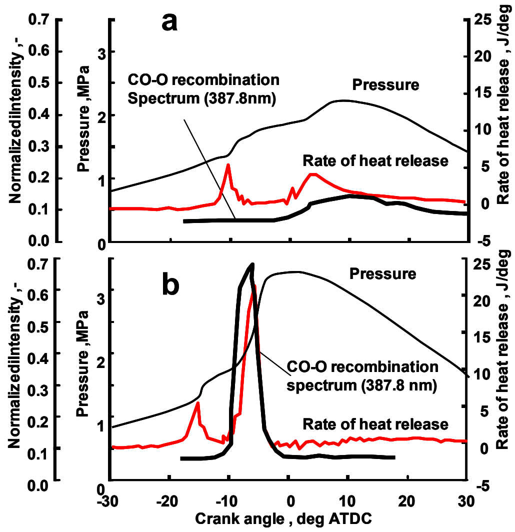

Fig. 6 CO-O recombination spectrum vs. rate of heat release