

Analysis of Supercharged HCCI Combustion Using a Blended Fuel

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ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) combustion has attracted much interest as a combustion system that can achieve both low emissions and high efficiency. But the operating region of HCCI combustion is narrow, and it is difficult to control the auto-ignition timing.

This study focused on the use of a two-component fuel blend and supercharging. The blended fuel consisted of dimethyl ether (DME), which has attracted interest as alternative fuel for compression-ignition engines, and methane, the main component of natural gas. A spectroscopic technique was used to measure the light emission of the combustion flame in the combustion chamber in order to ascertain the combustion characteristics. HCCI combustion characteristics were analyzed in detail in the present study by measuring this light emission spectrum. The effects of the combustion process on the engine operating characteristics were also investigated under the conditions of the two-component fuel blend and supercharging.

A spectroscopic measurement technique was used to obtain the light emission spectra of the combustion flame. The results showed that the application of supercharging moderated the recombination reaction of CO and O. Notably, it was observed that post-ignition heat release occurred in two stages with the blended fuel of DME and methane when supercharging was applied, depending on the quantity of methane injected. That is attributed to the occurrence of the combustion reactions of the two fuels at different times. As a result, the rate of the cylinder pressure rise was controlled, enabling stable high-load operation. Because the quantity of DME injected determines the ignition timing, the engine load level can be adjusted by means of the quantity of methane injected and supercharging to achieve ignition near top dead center. This suggests the possibility of obtaining stable operation at even higher loads.

INTRODUCTION

Recent energy circumstances and calls for reducing atmospheric emissions of carbon dioxide (CO₂) necessitate thoroughgoing measures to lower the levels of CO₂

originating in the combustion process of internal combustion engines and to facilitate operation on diverse energy sources. The Homogeneous Charge Compression Ignition (HCCI) combustion [1] process achieves combustion that is leaner than the lean flammability limit and also simultaneously reduces particulate matter (PM) and nitrogen oxide (NO_x) emissions [2]. This means that the HCCI process can provide combustion that is more efficient and cleaner than that of conventional engines. However, controlling the ignition timing of HCCI combustion is difficult because much of the process leading to ignition depends on chemical reactions. Complete combustion is poor in the low load region, resulting in high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions. Additionally, combustion takes place extremely rapidly in the high load region, so there is the issue of a limited operating load range. Various methods have been reported for resolving these issues, including the use of a blend of two fuels having different ignition characteristics [3-6], controlling the ignition timing by applying exhaust gas recirculation (EGR) [7, 8], and stratifying the fuel concentration [9].

In order to operate an engine stably in the high load region, it is necessary to increase the quantity of fuel injected. However, the increase is limited by the occurrence of rapid combustion that takes place when more fuel is injected under a condition of a constant intake airflow rate. Supercharging has attracted interest as a way of resolving this issue [10, 11]. The application of supercharging is an effective means of increasing the indicated mean effective pressure. Because supercharging increases the heat capacity of the in-cylinder gas, it can reduce the peak gas temperature. Moreover, the use of a fuel blend of dimethyl ether (DME) and methane, which have different ignition characteristics, can reduce the peak heat release rate [12]. However, the relationship between the mechanisms of HCCI combustion obtained with a two-component fuel blend and supercharging and the resultant engine operating characteristics is still not fully understood. Therefore, this study examined the effects of the mixing ratio of the fuel components, ignition timing and other parameters on HCCI combustion when a blended test fuel of DME and methane was used and supercharging was applied to increase the intake airflow rate. Combustion mechanisms were also examined using spectroscopic measurement techniques [13].

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EXPERIMENTAL PROCEDURE

TEST FUELS

The properties of DME and methane are given in Table 1. DME is looked to as a possible alternative fuel for compression ignition engines because its high cetane number allows smokeless operation [14]. It also has a negative temperature coefficient region, which induces heat release in multiple stages due to low-temperature and high-temperature oxidation reactions. Methane is the main component of natural gas that is regarded as a petroleum substitute. Additionally, methane does not autoignite easily because it has a cetane number of zero. Accordingly, the ignition characteristics of DME and methane are substantially different [3, 4]. In this study, DME and methane were injected into the intake pipe in a gaseous state for premixing.

Table 1 Properties of test fuels

Fuel	DME	Methane
Molecular Formula	CH_3OCH_3	CH_4
Cetane Number	>55	0
Lower Heating Value [MJ/kg]	28.8	50.3
Low Temperature Oxidation Reactions	Yes	No

Table 2 Specifications of test engine

4-cycle Air-cooled Single-cylinder Engine	
Bore×Stroke	76×66 mm
Displacement	299 cm ³
Valve Arrangement	OHV
Compression Ratio	11.5:1
Engine Speed	1400 rpm

EXPERIMENTAL EQUIPMENT

Table 2 gives the specifications of the test engine, and Fig. 1 shows the configuration of the test equipment schematically. A four-cycle, air-cooled single-cylinder engine was used in the experiments. The test engine was operated at a constant speed of 1400 rpm. The injection flow rates of DME and methane were controlled by mass flow controllers. A mechanically driven supercharger was installed in the intake pipe for varying the intake air pressure and intake airflow rate. The intake air temperature was adjusted by means of an intercooler installed in the intake pipe. A quartz crystal pressure transducer was installed in the cylinder head to measure the cylinder pressure. The combustion state was ascertained on the basis of exhaust gas measurements by using the Non - Dispersive Infrared (NDIR) Gas Analyzer.

Figure 2 shows the equipment that was installed in the cylinder head, cylinder and piston crown to obtain light emission and absorption measurements. Quartz observation windows were provided in spacer-like devices that were installed between the cylinder and the cylinder head.

Light emission measurement

Combustion flame light in the bore direction was extracted through quartz window A in Fig. 2 to observe the light emission behavior of the flame in the combustion chamber. The flame light extracted through this window was passed through an optical fiber cable and introduced into a monochromator in which it was separated at the target wavelength. The separated light was introduced into a photomultiplier tube to obtain the light emission intensity. Light emission spectra were acquired by using a variable-wavelength monochromator that made it possible to obtain the flame light at each wavelength of interest [15].

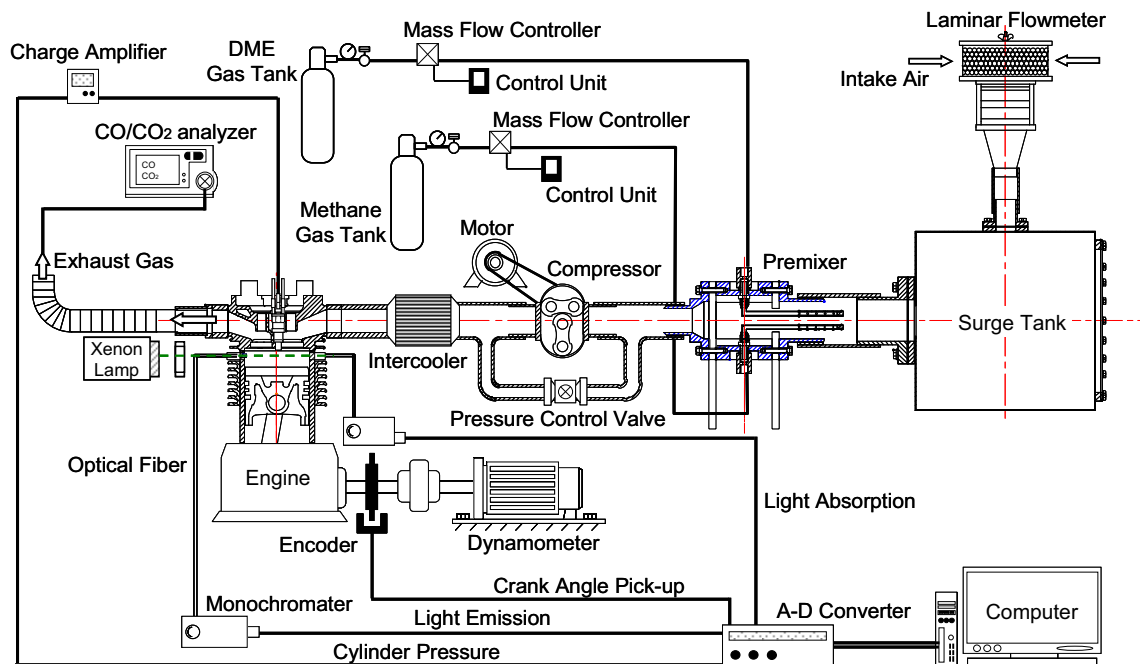


Fig.1 Configuration of experimental equipment

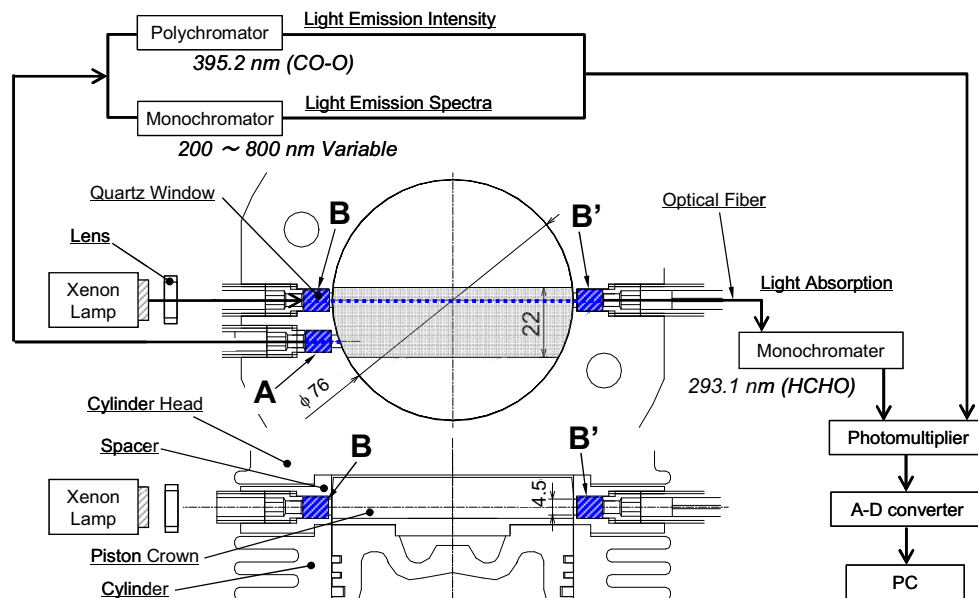


Fig.2 Configuration of spectroscopic system for making simultaneous light emission and absorption measurements in the bore direction in the cylinder

Light absorption measurement

The interior of the cylinder was irradiated with light from a xenon lamp through quartz window B in Fig. 2, and the transmitted light was extracted from quartz window B'. Using a monochromator, the transmitted light was separated at a wavelength of 293.1 nm [16] corresponding to the light absorption wavelength of formaldehyde (HCHO) that is a characteristic intermediate product of low-temperature oxidation reactions. The separated light was introduced into a photomultiplier tube and the device's output voltage $E_{293.1(\theta)}$ was used to define light absorbance $A_{293.1}$ as shown in the following equation. The notation $E_{293.1(0)}$ denotes the output voltage near bottom dead center.

Data were measured experimentally for 20 cycles and then averaged. The averaged values were used in the analysis.

$$A_{293.1} [-] = \frac{E_{293.1(0)} - E_{293.1(\theta)}}{E_{293.1(0)}}$$

EXPERIMENTAL RESULTS AND DISCUSSION

ANALYSIS OF LIGHT EMISSION SPECTRA OF DME

The light emission spectra of the combustion flame in the cylinder were analyzed to make clear the combustion characteristics of DME resulting from supercharging. The test fuel used in this experiment was DME alone. Table 3 shows the conditions under which the light emission spectra were measured. The injected heating value of the fuel was

kept constant at $Q_{DME} = 311$ J/cycle. Light emission of the combustion flame was measured and analyzed for two intake air pressure levels of 101 kPa and 142 kPa. The light emission spectra were obtained by recording the light emission intensity at wavelength intervals of 5 nm in a wavelength range of 200-800 nm during steady-state engine operation.

Figure 3 shows the typical heat release rate (HRR) waveform and the light emission intensity waveform E_{395} measured at 395 nm for each intake air pressure condition. As will be explained later, the 395-nm wavelength is in a bandwidth characterized by strong carbon monoxide-oxygen (CO-O) glow from the hot flame [16, 17]. The HRR waveforms measured for both intake air pressure conditions show the occurrence of heat release in two stages. The onset of the hot flame is defined here as beginning from the HRR rise due to the second-stage heat release. Compared with the results seen for the intake air pressure of $P_{in} (abs) = 101$ kPa, the HRR waveform for $P_{in} (abs) = 142$ kPa shows a lower peak HRR and more gradual heat release that continues in the second half of the hot flame phase (region C in Fig. 3). It is inferred that the higher intake air pressure increased the heat capacity of the in-cylinder gas, thereby moderating the temperature rise. As a result, the peak value of the mean in-cylinder gas temperature was reduced at the higher intake air pressure.

The light emission spectra obtained at each intake air pressure are shown in Figs. 4 and 5, respectively. The relationship between the crank angle, light emission intensity and wavelength is shown in a three-dimensional representation. In addition, the contours of the light emission intensity are projected in a three-dimensional representation at the bottom of each figure.

At the intake air pressure of 101 kPa in Fig. 4, overlapping light emission spectra with strong light emission intensities