

# Analysis of Combustion Characteristics and Efficiency Improvement of a Supercharged HCCI Engine Achieved by Using the Different Ignition Characteristics of Gaseous Fuels

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## ABSTRACT

This study focused on the use of a two-component fuel blend and supercharging as possible means of overcoming these issues of HCCI combustion. Low-carbon gaseous fuels with clean emissions were used as the test fuels. The specific fuels used were dimethyl ether (DME, cetane number of 55 or higher) that autoignites easily and exhibits pronounced low-temperature oxidation reactions, methane (cetane number of 0) that does not autoignite readily and is the main component of natural gas which is regarded as petroleum substitute, and propane (cetane number of 5) that is a principal component of liquefied petroleum gas. The results of previous investigations have shown that the use of a blended fuel of DME and methane produces a two-stage main combustion process under certain operating conditions, with the result that combustion is moderated. The mechanism involved in this process has been made clear by analyzing the exhaust gas using spectroscopic measurement methods and Fourier transform infrared (FTIR) spectroscopy.

The aim of this study was to examine the potential for further expanding the region of stable engine operation and improving thermal efficiency, to investigate the effective use of gaseous fuels, and to clarify the effects of different types of fuel on engine operating characteristics. Toward that end, HCCI combustion experiments were conducted and chemical kinetic simulations were run to analyze combustion characteristics in detail. The results revealed that main combustion occurred in two stages with the use of a blended fuel of DME and methane, resulting in more moderate combustion. In contrast, a two-stage main combustion process did not occur with a blended fuel of DME and propane, though it was observed that the overall combustion process was delayed.

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## 1. INTRODUCTION

Internal combustion engines have been required to attain higher efficiency and cleaner exhaust emissions in recent years owing to the growing severity of global environmental issues, including air pollution and the ongoing depletion of fossil fuel resources. The Homogeneous Charge Compression Ignition (HCCI) engine [1],[2],[3],[4],[5],[6] has attracted much interest and is being widely researched as a combustion system capable of achieving high efficiency and low emissions for addressing these issues.

Particulate matter (PM) emissions can be suppressed in an HCCI combustion system because a premixed mixture is inducted into the cylinder and burned, making it possible to

obtain a homogeneous fuel concentration distribution. Moreover, HCCI combustion is also advantageous for suppressing nitrogen oxide (NO<sub>x</sub>) emissions because combustion is possible in a lean mixture region that exceeds the normal limits of flame propagation.

However, there are several issues of HCCI combustion that remain to be resolved. For example, the HCCI engine has no physical means of controlling ignition like the spark plug of gasoline engines or the fuel spray of diesel engines, making it difficult to control the ignition timing. Additionally, heat release occurs very rapidly because the mixture autoignites simultaneously at multiple locations in the cylinder. As a result, the combustion process lacks

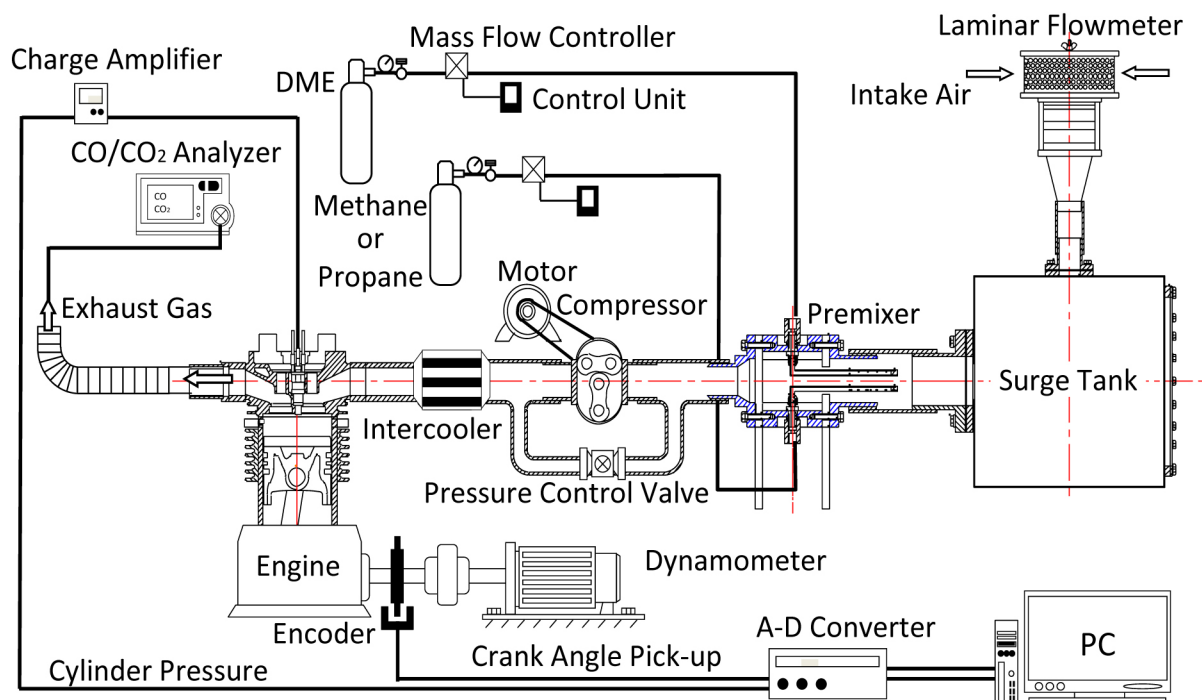


Figure 1. Configuration of test equipment

quietness and there is a likelihood of abnormal combustion occurring in the high load region. This study focused on the use of a two-component fuel blend [7],[8],[9] and supercharging [10]-[11] as possible means of overcoming these issues.

The results of our research to date have shown that the use of a fuel blend of dimethyl ether (DME) and methane results in heat release in two stages in the main combustion period under certain operating conditions, which has the effect of moderating combustion [12]. The mechanism producing this two-stage heat release behavior has been made clear using spectroscopic measurement techniques [13] and by exhaust gas analysis using Fourier transform infrared (FTIR) spectroscopy [14].

The purpose of this study was to make clear the effects of different types of fuel on HCCI engine characteristics with the aim of expanding the region of stable operation [15] [16], improving thermal efficiency and promoting effective use of gaseous fuels. Toward that end, HCCI combustion experiments were conducted and chemical kinetic simulations were also performed to analyze in detail and clarify the mechanisms involved.

## 2. TEST EQUIPMENT AND PROCEDURE

### 2.1. Test Equipment

The configuration of the test equipment used in the experiments is shown schematically in Figure 1. The specifications of the test engine and fuels used are given in

Table 1. The experiments were conducted with a four-cycle air-cooled single-cylinder engine. Mass flow controllers were used to control the flow rates of the gaseous test fuels to a premixer that premixed them with air before introduction into the engine where HCCI combustion took place. A constant engine speed of  $N = 1400$  rpm was used in this study. The intake air temperature was adjusted by means of a heater and an intercooler provided in the intake pipe, and the intake air pressure was adjusted with a mechanically driven supercharger. The tappet clearance was adjusted so that there was zero valve overlap in order to minimize the amount of fresh air that was blown out through the exhaust valve when supercharging was performed. A quartz crystal pressure transducer was installed in the cylinder head to measure the cylinder pressure.

### 2.2. Test Fuels

Three types of test fuels-DME, methane and propane-were used in the experiments. Table 2 shows the properties of the test fuels. Because of its high cetane number, DME autoignites easily and has low-temperature oxidation reaction mechanisms. It can be synthesized from various sources. Another characteristic of DME is that it does not produce soot when burned. Methane and propane, on the other hand, do not readily autoignite and display virtually no low-temperature oxidation reactions owing to their low cetane number. Methane is the principal component of natural gas that is seen as being a petroleum substitute, and propane is the main component of liquefied petroleum gas.

Table 1. Specifications of test engine and test fuels used

| 4-Cycle Single Cylinder Engine |                       |
|--------------------------------|-----------------------|
| Bore×Stroke                    | 76×66 mm              |
| Displacement                   | 299 cm <sup>3</sup>   |
| Compression Ratio              | 15 : 1                |
| Engine Speed                   | 1400 rpm              |
| Test Fuels                     | DME, Methane, Propane |

Table 2. Properties of test fuels

| Fuel                        | DME                              | Methane         | Propane                       |
|-----------------------------|----------------------------------|-----------------|-------------------------------|
| Molecular Formula           | CH <sub>3</sub> OCH <sub>3</sub> | CH <sub>4</sub> | C <sub>3</sub> H <sub>8</sub> |
| Cetane Number               | >55                              | 0               | 5                             |
| Lower Heating Value [MJ/kg] | 28.8                             | 50.3            | 46.5                          |

### 3. EXPERIMENTAL RESULTS AND DISCUSSION

#### 3.1. Combustion Characteristics of DME/Methane and DME/Propane Blends

Experiments were conducted in which the heating value of DME injected per cycle was kept constant while that of methane or propane was increased. With the aim of achieving higher efficiency, the compression ratio of the test engine was set at 15:1. The intake air pressure and temperature were kept approximately constant at  $P_b = 142$  kPa and  $T_{in} = 323$  K, respectively. The quantity of heat produced per cycle by the injected fuel ( $Q_{in}$ ) was constantly controlled to  $Q_{DME} = 160$  J/cycle so as to induce autoignition at top dead center (TDC). The experimental results for various blends of DME/methane and of DME/propane are shown in Figures. 2 and 3, respectively. From the top, both figures show the cylinder pressure  $P$ , heat release rate (HRR), maximum pressure rise rate  $dP/d\theta_{max}$  and the mean in-cylinder gas temperature  $T$ .

It is observed in Figure. 2 that heat release in the main combustion period occurred in two stages as the injected heating value of methane was increased. When the injected heating value of methane was increased further, the main combustion period was shortened by the occurrence of rapid combustion. Increasing the injected heating value of methane produced virtually no change in the ignition timing, as ignition took place near TDC in every case. In contrast, the results for propane in Figure. 3 show almost no evidence of two-stage heat release in the main combustion period with an increase in the injected heating value of this test fuel. It is seen that combustion occurred at a later time. Because the cylinder pressure also declined when  $Q_{total}$  was increased

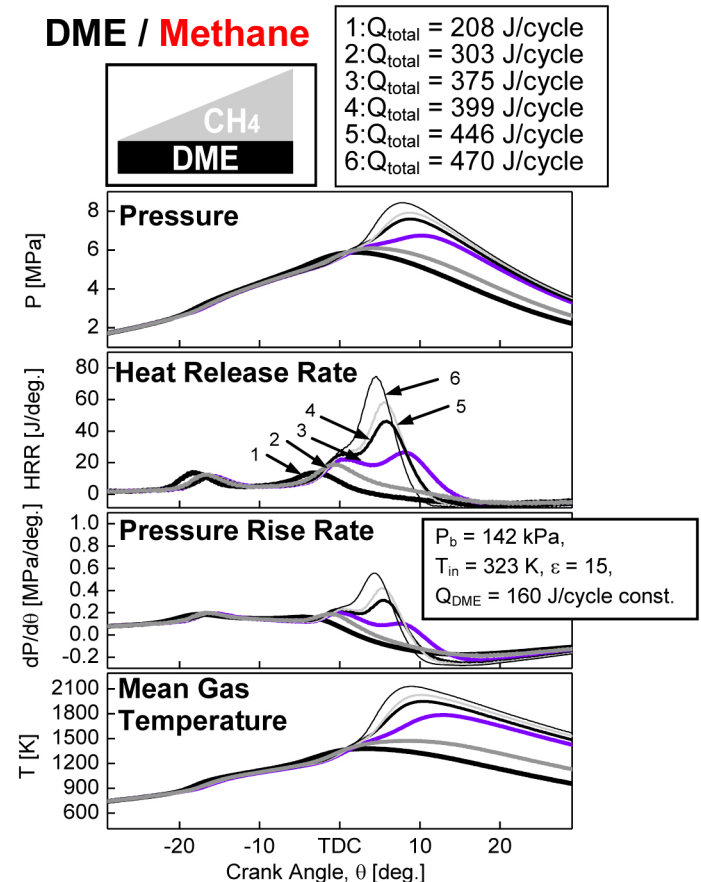


Figure. 2. Effect of DME/methane mixing ratio on combustion characteristics

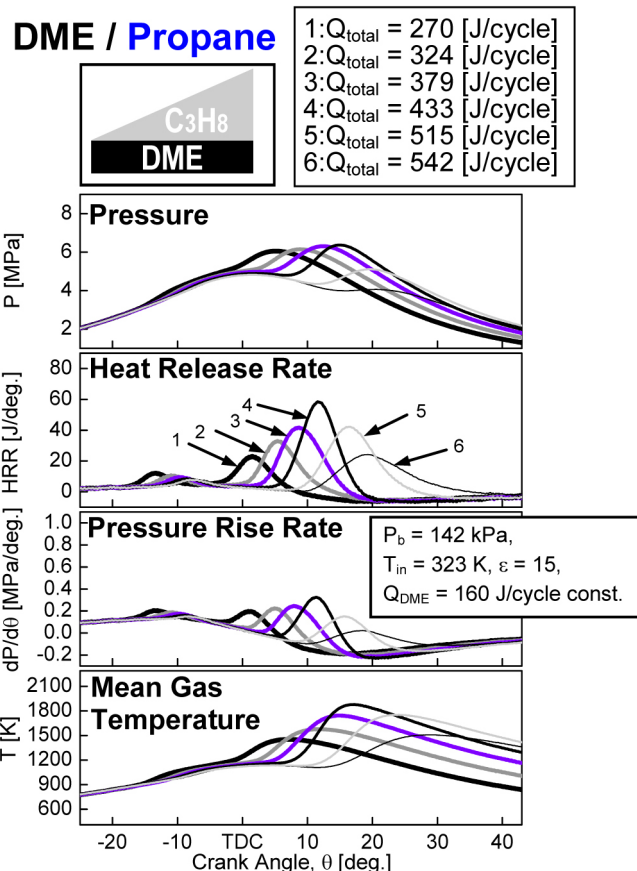


Figure 3. Effect of DME/propane fuel blends on combustion characteristics

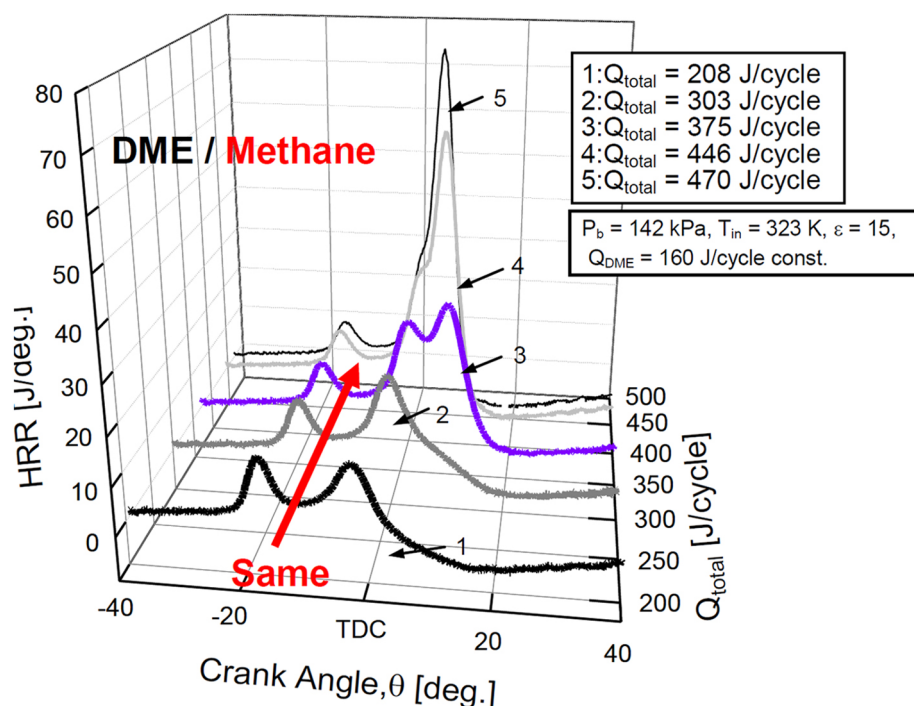


Figure 4. 3D representation of the effect of DME/methane mixing ratio on HRR