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Hydrogen as an ignition-controlling agent for HCCI combustion engine by suppressing the low-temperature oxidation

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Abstract

Homogeneous charge compression ignition (HCCI) combustion enables internal combustion engines to achieve higher thermal efficiency and lower NO_x emission than with conventional combustion systems. Controlling the ignition timing in accordance with the operating conditions is crucial for utilizing HCCI combustion engines. Adding hydrogen-containing gas is known to retard the autoignition of dimethyl ether (DME) considerably. The effective ignition control by hydrogen can expand the operation range of equivalence ratios and engine loads in HCCI combustion. This research investigated the mechanisms in the ignition control by the chemical kinetics analysis. The results show that the retarded ignition can be attributed to a consumption of OH by hydrogen during low-temperature oxidation of DME. The decreased OH concentration leads to retarded heat release and delays the onset of the high-temperature oxidation.

Keywords: Internal combustion engine; HCCI; Ignition control; Low-temperature oxidation; DME

1. Introduction

It is expected that the use of homogeneous charge compression ignition (HCCI) combustion in internal combustion engines will result in higher thermal efficiency and lower NO_x emissions than with conventional combustion systems. However, difficulties in controlling the ignition timing in accordance with the engine load prevent HCCI combustion from practical application in vehicle engines. Adjusting the proportion of two fuels with different ignition properties has been reported as an effective technique to control the ignition timing and load in HCCI combustion [1]. However, this technique has not been practically used in vehicles because of the inconvenience of carrying two kinds of fuels.

Dimethyl ether (DME) has been studied as a clean alternative to diesel fuel due to its high cetane number and smokeless combustion characteristics [2–4], and DME can be easily produced from methanol by the dehydration reaction [5]. A report suggests using a small amount of DME produced from methanol as an ignition promoter in a methanol direct-injection diesel engine [2]. Methanol can also be thermally decomposed into methanol reformed gas (MRG) which consists of hydrogen and carbon monoxide. Since both hydrogen and carbon monoxide have good anti-knocking properties [6], MRG has been studied as a fuel for spark-ignition engines [7,8].

With this background, an HCCI combustion engine system that was fueled with DME and MRG has been proposed [9–11]. Because the ignition properties of DME and MRG are very different, adjusting the proportion of the two fuels can control the ignition timing in an HCCI combustion engine fueled with the two. In addition to ignition control, production of DME and MRG by onboard reformers utilizing the exhaust gas heat of the engine has also been proposed, with an outline of the arrangement as shown in Fig. 1. Because the reactions to produce DME and MRG from methanol are endothermic, the heating values of the produced DME and MRG can be higher than the primary fuel. Therefore, methanol reformation using the engine exhaust gas heat could be utilized to recover waste heat from the engine. By combining efficient HCCI operation and waste heat recovery, a system based on these processes can achieve a good overall thermal efficiency. The use of a single-liquid fuel,

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Nomenclature

ε	compression ratio
ϕ	equivalence ratio
θ	crank angle
P	in-cylinder pressure
$dQ/d\theta$	apparent rate of heat release
Q	cumulative apparent heat release
η_i	indicated thermal efficiency
T_g	in-cylinder gas mean temperature
LTR	low-temperature reactions
HTR	high-temperature reactions
T_{LTR}	T_g at the beginning of LTR
T_{HTR}	T_g at the beginning of HTR
θ_{LTR}	crank angle at the beginning of LTR
θ_{HTR}	crank angle at the beginning of HTR
HCCI	homogeneous charge compression ignition
DME	dimethyl ether
MRG	methanol-reformed gas
MeOH	methanol
MFC	mass flow controller
EGR	exhaust gas recirculation
IMEP	indicated mean effective pressure
THC	total hydrocarbon
CA	crank angle
ATDC	after top dead center

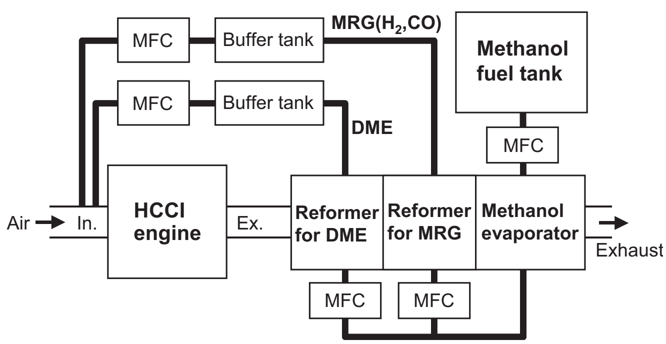

Fig. 1. Concept of HCCI combustion engine system fueled with DME and MRG onboard-reformed from methanol.

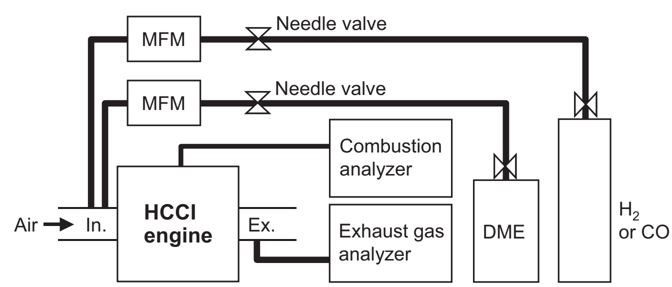

Fig. 2. Schematic diagram of experimental system.

methanol, also eliminates the inconvenience of having to carry two fuels and makes the HCCI combustion practically possible in vehicles. It is crucial to avoid a too early ignition to achieve higher load operation in HCCI engines, and hydrogen retards the autoignition of DME considerably [10,11]. The ignition control effect by MRG is attributed to the hydrogen in MRG. Therefore, DME-reformed gases, which contain hydrogen, are also effective to control autoignition of DME [12]. This report investigates the reaction mechanisms in the ignition control of hydrogen by using chemical kinetics analysis.

2. Experiments and calculations

The test engine used was a four stroke cycle single-cylinder engine with a bore of 85 mm, a stroke of 88 mm and a compression ratio of 9.7. The fuel gases, dimethyl ether (DME; CH_3OCH_3) and hydrogen (H_2), were stored in high-pressure cylinders and continuously supplied to the intake manifold of the engine as shown in Fig. 2. Fuel flow rates were separately controlled using needle valves and measured by massflow meters (Oval). The in-cylinder pressure was measured with a piezoelectric pressure transducer (AVL GM12D) installed in the cylinder head. For each experimental condition, the pressure data for 100 cycles were averaged and used to calculate the mean in-cylinder gas temperature, the indicated mean effective pressure, the indicated thermal efficiency and the apparent rate of heat release. Concentrations of CO and THC in the exhaust gas were measured with an NDIR analyzer, and an FID analyzer, respectively. The engine speed was set at 1000 rpm for all the experiments. The volumetric efficiency was controlled at 75% including fuel gases. The intake air was at room temperature without heating.

A chemical kinetics analysis using CHEMKIN II was performed to analyze the reaction mechanisms in the ignition control effect of hydrogen. The detailed reaction mechanism for DME oxidation reported by Curran et al. [13,14] was employed in SENKIN adiabatic calculations. Volume changes and initial conditions for the calculation were determined according to the engine experiments.

3. Results and discussions

3.1. Experimental results of ignition control by hydrogen in HCCI combustion

Previous research [9] has shown that MRG, which consists of hydrogen and carbon monoxide, has a large ignition control effect on HCCI combustion of DME. Fig. 3 shows the effects of hydrogen and carbon monoxide on HCCI combustion of DME. The DME amount was fixed at a value that gives the equivalence ratio of 0.27 without the addition of hydrogen or carbon monoxide. The mole fraction of hydrogen or