

Improvement in DME-HCCI Combustion with Ethanol as a Low-Temperature Oxidation Inhibitor

Hu Zhang, Ryo Hasegawa and Hideyuki Ogawa
Hokkaido University, Sapporo Japan

Copyright © 2011 Society of Automotive Engineers of Japan, Inc. and Copyright © 2011 SAE International

ABSTRACT

Port injection of ethanol addition as an ignition inhibitor was implemented to control ignition timing and expand the operating range in DME fueled HCCI combustion. The ethanol reduced the rate of low-temperature oxidation and consequently delayed the onset of the high-temperature reaction with ultra-low NO_x over a wide operating range. Along with the ethanol addition, changes in intake temperature, overall equivalence ratio, and engine speed are investigated and shown to be effective in HCCI combustion control and to enable an extension of operation range. A chemical reaction analysis was performed to elucidate details of the ignition inhibition on low-temperature oxidation of DME-HCCI combustion.

INTRODUCTION

Homogeneous charge compression ignition (HCCI) combustion has attracted much attention due to its potential advantages in achieving ultra lean burning with high thermal efficiency, simultaneous with ultra low emissions of nitrogen oxides (NO_x) and particulate matter (PM), all advantages that are attractive in terms of fuel economy, environmental impact, and engine design [1, 2].

However, HCCI combustion suffers from a number of weaknesses, principally the difficulty in combustion phasing control, arising from the combustion mechanism of HCCI, where the combustion reaction exclusively depends on the chemistry of the air-fuel mixture. There is no active method to control the start of combustion, however, several passive potentially possible control methods have been proposed: varying the rate of exhaust gas recirculation (EGR) [3], using variable valve timing (VVT) to capture a proportion of the hot exhaust gases in the engine cylinder [4], using a variable compression ratio (VCR) to change the effective compression ratio [5], changing the engine speed to control the time available for reactions [6], and using additives to take advantage of the resulting fuel modification [7, 8]. Of these measures to control ignition timing, the use of additives is the most promising and has been proposed by Ricklin et al., who noted that differences in the chemical components or

ignitability could be employed to achieve a wide range of HCCI timing control. Lv et al. also confirmed this [9, 10], as the onset timing of the low-temperature reaction (LTR), the heat release rate (HRR), rising temperature, and pressure during the LTR significantly influence the high-temperature reaction (HTR). This would suggest that controlling the LTR by inhibitor offers an avenue ahead to broaden the operating range of HCCI combustion.

With this background, some reports have addressed ignition control of HCCI combustion using reaction inhibitors. Ogawa et al. attempted the control of onset timing and suppression of excessively rapid combustion in a light naphtha fueled HCCI with direct in-cylinder injection of water, methanol etc. as the ignition inhibitors, of which, alcohols have been found effective in inhibiting LTR. In his research, expansion of the available operating range to a level comparable with ordinary diesel operation was achieved by the optimization of timings and quantities of injected water and methanol [11, 12]. Shudo et al. reported the detailed mechanism in combustion phasing control with hydrogen used as the ignition inhibitor, and also showed that carbon monoxide together with hydrogen have the positive effect of retarding the onset of HTR [13, 14]. Yamada et al. proposed methanol and ozone as additives in DME fueled HCCI combustion, and detailed the mechanisms controlling the combustion. These results indicated that the HCHO+OH and methanol+OH reactions are responsible for the termination of the DME chain reaction in LTR, and that ozone has a negative effect on retarding the onset of HTR as a result of the delay on HCHO formation [15]. Chen et al. tried to control the onset timing of HCCI combustion by varying the DME/natural gas ratio in concert with the engine load [16].

Generally, the high volatility or gaseous fuels is an attractive factor in their use as basic fuels for HCCI, but the ignitability of highly volatile and gaseous fuels is generally too low for compression ignition. Here, dimethyl ether (DME) appears to be an exception among gaseous fuels as it has sufficient ignitability with a cetane number above 55, and can simply be obtained from methanol by dehydration [17], due to this it has been widely used in HCCI combustion research. In addition, other fuels have also been used in HCCI

engines as the basic fuel, fuels such as diethyl ether (DEE) [18-20], n-heptane [21], and liquefied petroleum gas [22]. As inhibitors, other than hydrogen, carbon monoxide, methanol, water, and others, ethanol has also been widely used [11], as ethanol is a renewable energy source, which can be produced from many kinds of raw materials.

In this paper, ethanol was introduced into a DME fueled HCCI engine from the intake pipe as an inhibitor and the effects of ethanol addition on DME-HCCI combustion were investigated in terms of the onset timings of LTR and HTR (θ_{LTR} , θ_{HTR}), heat release of LTR (Q_L), and duration of HTR (HTRD) and emission characteristics. The investigations are at the same time performed under different intake temperatures and overall equivalence ratios. As the main concern in the issues around HCCI combustion, experiments attempting to expand the operation range by controlling the intake temperature and engine speed were also performed. The mechanism of the inhibition effect is investigated by the chemical kinetics analysis.

EXPERIMENTS AND CALCULATIONS

EXPERIMENTAL SETUP

The specifications of the engine used in this study are listed in Table 1, and the experimental apparatus is shown in Fig. 1. Dimethyl ether (DME) was continuously introduced into the intake pipe and ethanol was injected into the intake pipe 0.85 m upstream from the cylinder head to form a highly premixed homogeneous charge. The intake air was electrically heated after the damping chamber, and the temperature of fuel-air mixture at the intake port was constantly controlled. The in-cylinder pressure was measured with a piezoelectric pressure transducer installed in the cylinder head with a time resolution of 0.2°C. The output change from the transducer was converted to an amplified voltage. For each measuring point, the pressure data of 45 consecutive cycles were sampled and averaged for calculations of the in-cylinder gas temperature, the indicated mean effective pressure, the indicated thermal efficiency, and the rate of heat release. The exhaust gas was sampled and measured by an MEXA-9100DEGR (HORIBA) emission analyzer. Other operating conditions included an engine speed of 1000 rpm and a coolant temperature of 80°C.

DEFINITION OF COMBUSTION PARAMETERS

The onsets of LTR and HTR are defined as the points of intersection of the horizontal axis and the tangent of the point where the gradient is the maximum on the respective rising side of the curve of the heat release rate. The end of the LTR is defined as the point where the heat release rate reaches the lowest level after LTR. The end of the HTR is defined as the crank angle corresponding to 20% of the magnitude at the peak of heat release on the falling side of the curve. The duration of HTR (HTRD) is defined as the angle of the interval between the onset and the end of HTR. The heat release during LTR is obtained by integrating the

heat release rate during the angle of the interval between the onset and the end of LTR.

Table 1 Engine specifications

Engine type	Nissan SC-77
Number of cylinders	Single cylinder
Bore × stroke	85.0 mm×88.0 mm
Number of valves	1 inlet valve, 1 exhaust valve
Displacement	499 cm ³
Compression ratio	10.8

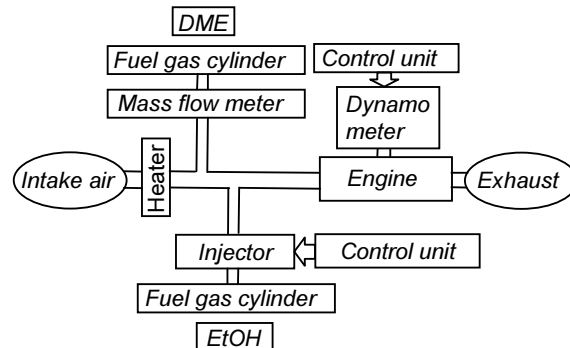


Fig. 1 Experimental apparatus

CHEMICAL KINETICS

The combustion inhibition mechanism with ethanol in DME-HCCI combustion was analyzed with chemical kinetic modeling, as proposed by Curran et al. [23] and Williams et al. [24]. The CHEMKIN PRO was employed to compute the time evolution of reacting homogeneous gas mixture in a closed system. This system was modeled zero-dimensionally under the assumptions that the gas mixture was completely homogeneous and the reactions occurred in under adiabatic conditions. Volume changes and initial conditions for the calculations were determined from the engine experiments.

EXPERIMENTAL RESULTS AND DISCUSSIONS

IGNITION CONTROL WITH ETHANOL ADDITION IN DME-HCCI COMBUSTION

Fig. 2 shows the effects of the ethanol fraction on HCCI combustion of DME under an intake temperature of 20°C. The overall equivalence ratios of all cases were fixed at 0.30. The energy fraction of the ethanol addition in the total input energy was varied from 0% to 20%. For all cases, the typical HCCI combustion features including two-stage combustion and negative temperature coefficient (NTC) are observed. With the increase in ethanol addition, inhibited LTR and retarded onset of HTR are achieved. This suggests the possibility of a controllable ignition timing that enables combustion to occur in accordance with the operating conditions. The inhibition due to ethanol is further elaborated by observing the onset crank angles of both

LTR and HTR, the heat release of LTR (Q_L) and the duration of HTR (HTRD) as shown in Fig. 3, where the results with a further two intake temperatures are shown as well.

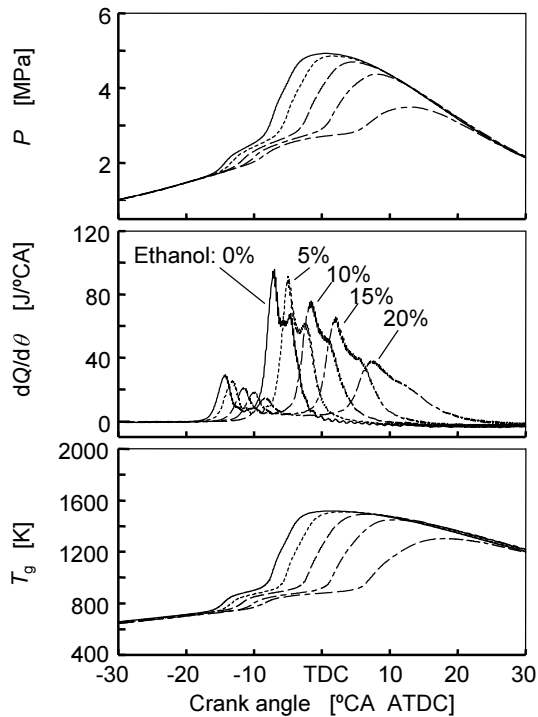


Fig. 2 Influence of ethanol fraction on HCCI combustion of DME with ethanol addition ($\phi_{\text{all}} = 0.3$, $T_{\text{intake}} = 20^\circ\text{C}$, 1000 rpm)

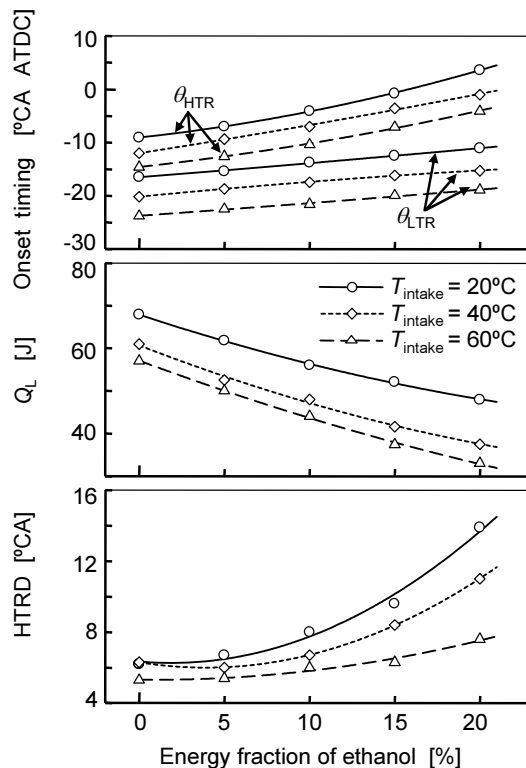


Fig. 3 Influence of ethanol fraction on the onset timings of LTR and HTR (θ_{LTR} , θ_{HTR}), heat release of LTR (Q_L) and duration of HTR under different intake temperatures, T_{intake} ($\phi_{\text{all}} = 0.3$, 1000 rpm)

INHIBITION WITH ETHANOL IN HCCI COMBUSTION UNDER VARIOUS INTAKE TEMPERATURES

In Fig. 3, the onset crank angles of both the LTR and HTR are increasingly retarded with the increase in energy fraction of the ethanol addition under a specific intake temperature. The retardation in HTR is more pronounced than the retardation in LTR, successfully pushing the main combustion back to around the TDC in a relatively wider range. The onset delay of LTR can be attributed to two main reasons. The primary reason is the low ignitability of ethanol that causes the ignition delay directly and another reason is the effect of the evaporation of ethanol that lowers the in-cylinder gas temperature. Together with the decreased heat release during the LTR, a more obvious delay in HTR is achieved as shown in Fig. 3. As a crucial parameter of combustion, the duration of the HTR is also investigated here. By introducing the ethanol, an extended HTRD can be expected. It is mainly due to the delayed onset timing of the HTR, which makes a part of combustion occur during the expansion stroke. A properly delayed onset timing of HTR along with a relatively longer HTRD enables the engine to operate under quite low emissions and high efficiency as shown in the following figures. Here, the change in the intake temperature also changes the charge mass of the mixture under the same equivalence ratio and intake pressure, leading to the decrease in the heat release during LTR. Normally, the increase in temperature accelerates the overall reaction rate following the Arrhenius equation of kinetics. Therefore, the onset crank angles of both the LTR and HTR tend to be earlier, and the HTRD tends to be shorter owing to the increased mean temperature during HTR mainly caused by compression effect before TDC at a higher intake temperature.

Fig. 4 shows the effect of ethanol addition on the indicated mean effective pressure, IMEP, the indicated thermal efficiency, η_i , $dp/d\theta_{\text{max}}$ and coefficient of variation of IMEP, COV, under different intake temperatures. In all three cases of the intake temperatures here (20, 40, 60°C), the IMEP increase is accompanied by an increased η_i with gradually decreased noise with the ethanol fraction below 15% of the energy addition. This can be attributed to the well controlled onset timing of HTR shown in Fig. 3, making the main combustion occur closer to TDC. Nevertheless, when the energy fraction of the ethanol addition increases to 20%, combustion in the cylinder turns to be unstable ($\text{COV} > 5\%$), sudden drops at both IMEP and η_i for the case of 20°C are observed. This can be due to the too late onset timing of HTR, making the whole combustion occur during the expansion stroke. A similar trend is also seen in the case of intake temperature of 40°C. As to the effect of intake temperature here, under a specific energy fraction of ethanol addition, the decrease in IMEP is for the same reason as the decrease in Q_L . A much earlier onset timing of HTR and shorter HTRD with a higher intake temperature result in lower η_i , however, in comparison with the lower intake temperature cases, a further increase in η_i with intake temperature 60°C to a comparable level with the ethanol addition above 20% can be expected. In this sense, an increase in intake