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IMPACT OF FORMALDEHYDE ADDITION ON AUTO-IGNITION IN INTERNAL-COMBUSTION ENGINES

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ABSTRACT

By employing a direct-injection diesel engine equipped with a common-rail type of in- jection system, by adding formaldehyde (CH2O) to the intake air, and by changing the fuel- injection timing, the compression ratio and the intake-air temperature, a mechanism for CH2O as a fuel additive to affect auto-ignition was discussed. Unlike an HCCI type of engine, the diesel engine can expose an air-fuel mixture only to a limited range of the in-cylinder temper- ature before the ignition, and can separate low- and high-temperature parts of the mechanism. When low-temperature oxidation starts at a temperature above 900 K, there are cases that the CH2O advances the ignition timing. Below 900 K, to the contrary, it always retards the tim- ing. It is because, above 900 K, a part of the CH2O changes into CO together with H2O2 as an ignition promoter. Below 900 K, on the other hand, the CH2O itself acts as an OH radi- cal scavenger against cool-flame reaction, from the beginning of low-temperature oxidation. Then, the engine was modified for its extraordinary function as a gasoline-knocking gener- ator, in order that an effect of CH2O on knocking could be discussed. The CH2O retards the onset of auto-ignition of an end gas. Judging from a large degree of the retardation, the ignition is probably triggered below 900 K.

Key Words: Internal Combustion Engine, Ignition, Combustion, Auto-Ignition, Spray Combustion, Knocking, Ignition Control, Additive, Formaldehyde, Flame Light Emissions

1.Introduction

There are auto-ignition dominated subjects of combustion in internal combustion engines, that is, those of combustion control for homogeneous-charge compression-ignition (HCCI) types of engines, knocking control for gasoline engines, and new combustion modes for diesel engines to reduce both NOx and smoke emis- sions. Especially of HCCI engines, a lot of researchers

have been making efforts to resolve one of its difficult problems, how to control the ignition timing and stabi- lize the sensitive timing, as they recognized its poten- tial advantages of a high thermal efficiency and very-low NOx and zero smoke emission levels. Effects of directly- controllable factors such as fuel properties and engine-operating conditions of the intake-air temperature, the compression ratio, the air-fuel ratio and the EGR ratio on the ignition have been investigated. As another approach to HCCI timing control, ideas of making use of a fuel ad- ditive, for example, hydrogen peroxide(1) or ozone(2) as an ignition promoter, and formaldehyde(3) – (5) or methanol(2) as an ignition retardant, have been proposed. By Aceves et al. with the aid of calculation involving one-dimensional hydrodynamics transport and detailed chemical kinetics, hundreds of potential additives were ranked according to their capabilities for advancing the ignition timing(6).

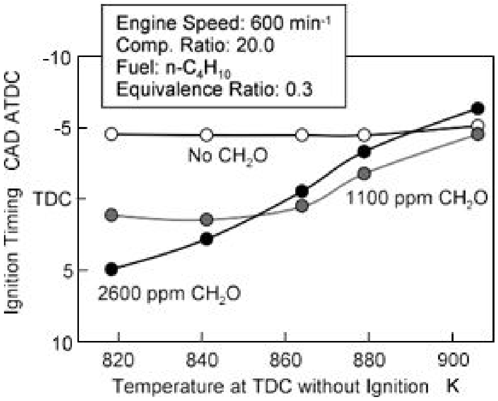


Fig. 1 Effect of CH_2O addition on ignition timing of air n-C_4H_{10} mixture$^{(4)}$

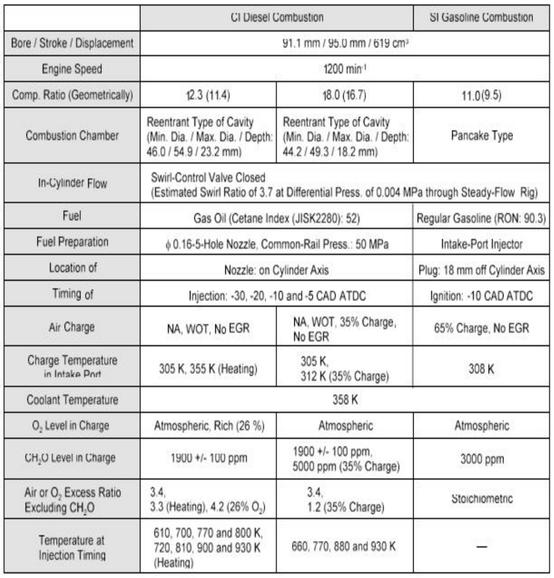
2.Experimental Procedure

2.1 Test engine and its operating conditions

A four-valve single-cylinder naturally-aspirated direct-center-injection diesel engine equipped with a common-rail type of injection system, was supplied for this study. A pressure transducer (AVL GU12S-10) was mounted on the cylinder head, in place of the glow plug. The intake-air temperature was measured 70 mm upstream of an intake valve. A part of the exhaust gas was by-passed into an exhaust-gas analyzer (Horiba MEXA-8220D). Table 1 lists specifications of the engine together with its operating conditions. In a conventional use of the engine fueled with gas oil (cetane index (JISK2280): 52), the compression ratio was set at 18.0 or

12.3. The fuel-injection timing was changed between 30 and 5 crank-angle degrees (CAD) ATDC. The injection timing of 30 CAD ATDC is close to the limit of the advancement, for fuel sprays out of the multi-hole nozzle to be captured within the piston cavity. But also, conve- niently, it is almost coincident with a timing before which any cool flame could not appear at the low compression ratio, even in case of HCCI. There was also a case at the low compression ratio, that the intake-air temperature was increased by 50 K using a heater installed upstream of the intake manifold, in order that the in-cylinder temperature at TDC only with the air could be almost the same as that at the high compression ratio without any heating. In these ways, a temperature to which an air-fuel mixture was exposed before the auto-ignition, was changed between 660 and 930 K at a rough estimate with the intake-air temperature without any consideration of a residual gas and a heat loss. In another case at the low compression ratio, O2 was added to the intake air, and its level in the charge was increased up to 26.0%, so that the difference could be discussed, when the ignition delay was shortened by the high temperature or by the high O2 level.

Table 1 Engine specifications and operating conditions



	CI Diesel Combustion		SI Gasoline Combustion
Bore / Stroke / Displacement	91.1 mm / 95.0 mm / 619 cm^3		
Engine Speed	1200 min^{-1}		
Comp. Ratio (Geometrically)	12.3 (11.4)	18.0 (16.7)	11.0(9.5)
Combustion Chamber	Reentrant Type of Cavity (Min. Dia. / Max. Dia. / Depth: 46.0 / 54.9 / 23.2 mm)	Reentrant Type of Cavity (Min. Dia. / Max. Dia. / Depth: 44.2 / 49.3 / 18.2 mm)	Pancake Type
In-Cylinder Flow	Swirl-Control Valve Closed (Estimated Swirl Ratio of 3.7 at Differential Press. of 0.004 MPa through Steady-Flow Rig)		
Fuel	Gas Oil (Cetane Index (JISK2280): 52)		Regular Gasoline (RON: 90.3)
Fuel Preparation	ϕ 0.16-5-Hole Nozzle, Common-Rail Press.: 50 MPa		Intake-Port Injector
Location of	Nozzle: on Cylinder Axis		Plug: 18 mm off Cylinder Axis
Timing of	Injection: -30, -20, -10 and -5 CAD ATDC		Ignition: -10 CAD ATDC
Air Charge	NA, WOT, No EGR	NA, WOT, 35% Charge, No EGR	65% Charge, No EGR
Charge Temperature in Intake Port	305 K, 355 K (Heating)	305 K, 312 K (35% Charge)	308 K
Coolant Temperature	358 K		
O_2 Level in Charge	Atmospheric, Rich (26 %)	Atmospheric	Atmospheric
CH_2O Level in Charge	1900 +/- 100 ppm	1900 +/- 100 ppm, 5000 ppm (35% Charge)	3000 ppm
Air or O_2 Excess Ratio Excluding CH_2O	3.4, 3.3 (Heating), 4.2 (26% O_2)	3.4, 1.2 (35% Charge)	Stoichiometric
Temperature at Injection Timing	610, 700, 770 and 800 K, 720, 810, 900 and 930 K (Heating)	660, 770, 880 and 930 K	—

Next to the indicator measurement, the engine was modified for detection of flame light emissions. One out of two exhaust valves was removed. Instead of the valve and the pressure transducer, a quartz-glass biconcave window with a diameter of 8.0 mm, a thickness of 16.0 mm and a concave radius of 6.6 mm on the both sides, was mounted at an offset of 18.0 mm from the axis of the cylinder and on the axis of one of fuel sprays. A quartz-glass fiber bundle with a diameter of 1.0 mm and a light collection angle of 23 degrees was coupled with the window. A time-series of 228 lines of light emission spectra in a wavelength range between 300 and 580 nm were acquired in a single cycle at a sampling rate of 0.25 or 2.0 CAD, using a high-speed optical multi-channel analyzer(7). Unfortunately, however, a local cool flame was either too faint to be detected using the optics, or was off from the light collection volume.

Then, the engine was used as a knocking genera- tor charged with an air-gasoline (research octane number: 90.3) homogeneous mixture. A spark plug with a built-in pressure transducer on its seat (trial product) was mounted in place of the window, that is, at an offset of 18.0 mm from the cylinder axis. The piston was replaced with a flat-top one. A conventional gasoline-engine injector was installed between the intake-air heater and the location of the CH2O addition. The CH2O was at a level of 3 000 ppm in the stoichiometric mixture, equivalent to 1/22 of the amount of gasoline in weight.

2.2 Formaldehyde feed

CH2O-feeding conditions were set equally to those in the previous studies. In the studies, a part of in- cylinder gas had been directly sampled, and the level of CH2O in it had been measured using a gaschromatograph equipped with a flame ionization detector (GL Science GC-390TTDF)(3), (4). The previous data could be used for calibration on the level of CH2O in this study.

The amount of CH2O was monitored also by means of its value derived from the difference in the total amount of C atoms in exhaust emissions with or without the CH2O addition. Its validity is dependent on a previous result that, even in an extremely-lean HCCI engine, almost all of added CH2O is oxidized into CO and CO2 during the combustion, which are detectable using the exhaust-gas analyzer, as shown in Fig. 2(4).

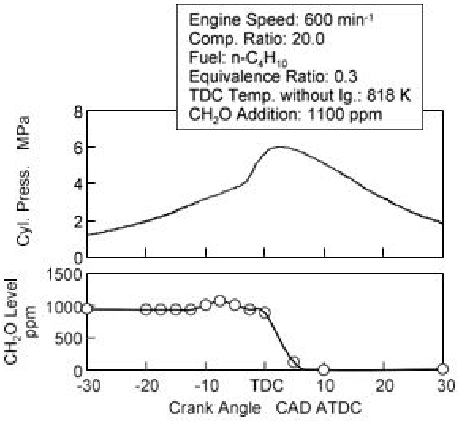


Fig. 2 History of in-cylinder CH_2O level in case of HCCI engine fueled with n-C_4H_{10}(4)

3.Results and Discussion

3.1 Effect on formaldehyde addition on auto-ignition in diesel engine

Figures 3 to 5 show histories of the in-cylinder pressure and the effective heat release rate (EHRR) with or without the CH2O addition, at the different compression ratios and charge temperatures, acquired every 0.125 CAD over continuous 30 cycles and cycle-averaged. Figure 6 shows ignition delays from the fuel-injection timings. Here, the ignition timing was defined as the timing when the gradient of an EHRR history first reaches 0.02 MPa/CAD2 (12.4 J/CAD2) in an empirical way. Cool-flame reaction or faint heat release before the ignition appears at the same timing with or without the CH2O, as drawn with a single dotted line. At the low compression ratio, the CH2O weakens the pre-ignition heat release, and retards the ignition timing with any injection timings, compared to that without any addition. This is remarkable with the earliest injection timing when a two-stage type of heat release characterized by cool-flame reaction, appears.

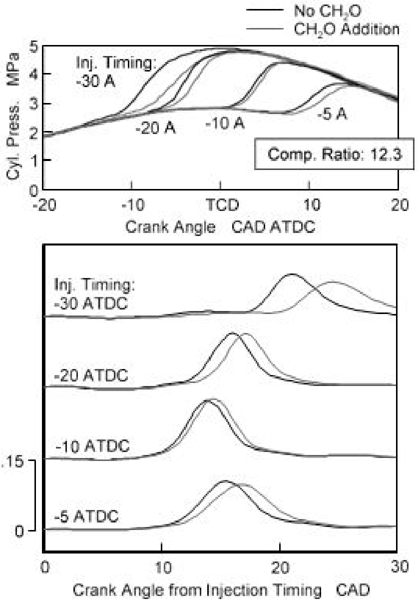


Fig. 3 Histories of in-cylinder pressure and effective heat-release rate in case of low compression ratio

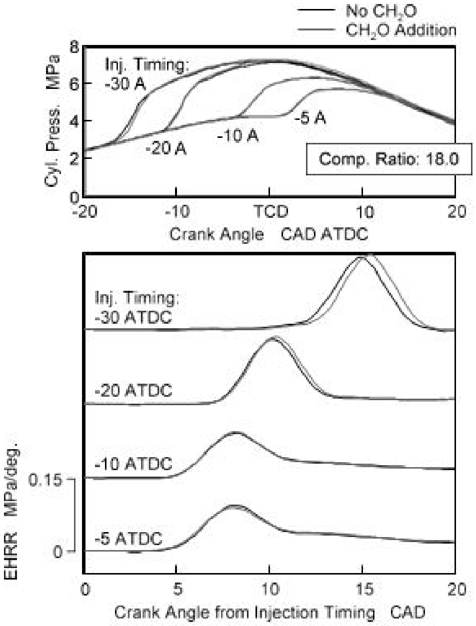


Fig. 4 Histories of in-cylinder pressure and effective heat-release rate in case of high compression ratio

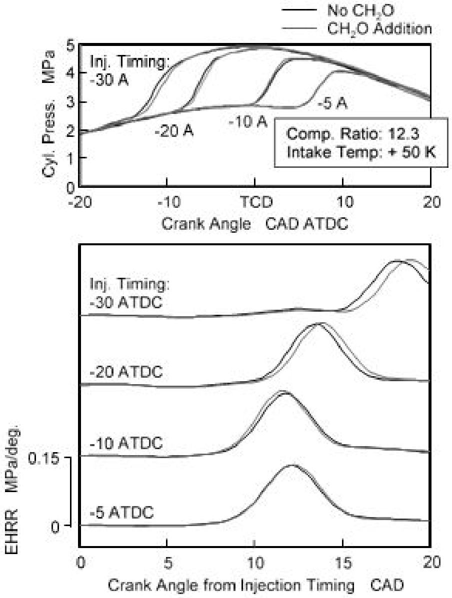


Fig. 5 Histories of in-cylinder pressure and effective heat-release rate in case of low compression ratio and heating

What is interesting in the figure, is that, although the added O2 always shortens the ignition delay as a whole, compared to that at the atmospheric O2 level, unexpect- edly, it can be a retardant against the start of cool-flame reaction with the earliest injection timing. Looking back at Fig. 6, the high compression ratio also retards the start of pre-ignition reaction with the earliest injection timing.

Figure 8 shows histories of the in-cylinder pressure and the EHRR, when the intake air was throttled at the high compression ratio. Even though the ignition delay is longer than that at the low compression ratio, the CH2O addition still advances the ignition timing. Although a two-stage type of heat release appears, the CH2O does not weaken the pre-ignition heat release as it does at the low compression ratio. The advancement is remarkable with the injection timing of 5 CAD ATDC when the ignition delay is much extended.

4.Conclusions

For close discussion about a mechanism for CH2O as a fuel additive to interact with auto-ignition of an air-fuel mixture, a direct-injection diesel engine equipped with a common-rail type of injection system was employed. It is because, unlike an HCCI engine, it can expose a mix- ture only to a limited range of the in-cylinder temperature before the ignition, and therefore, can separate low- temperature and high-temperature parts of interaction of CH2O, that is, parts interacting with cool-flame reaction and blue-flame reaction. Vapor of CH2O was added to the intake air. The ignition was induced at different fuel-injection timings, compression ratios and intake-air tem- peratures, that is, at different in-cylinder temperatures. Light emission spectra at the ignition timing were detected.

When low-temperature oxidation starts at a tempera- ture above 900 K, there are cases that the CH2O addition advances the ignition timing. Below 900 K, to the contrary, it always retards the timing. In case of the remark- able retardation, the CH2O completely eliminates the OH radical emission. After all, the experimental results of the ignition timing are consistent with those using an HCCI engine in Fig. 1. This means that in case of the advance- ment of the HCCI timing, the interaction of CH2O with cool-flame reaction is negligible for the timing.

The opposite effects of the CH2O on the ignition delay were most simply modeled. Above 900 K, a part of the CH2O is changed into CO and H2O2, and the latter acts as an OH radical generator in the final stage of low-temperature oxidation. Below 900 K, on the other hand, the CH2O itself acts as an OH radical scavenger against cool-flame reaction, from the beginning of low- temperature oxidation.

Then, the engine was modified for its extraordinary function as a gasoline-knocking generator, in order that an effect of CH2O on knocking could be discussed. The CH2O retards the onset of auto-ignition of an end gas. Judging from a large degree of the retardation, the ignition is probably triggered below 900 K.

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