FORMALDEHYDE FOR THE PREMIXED COMPRESSION-IGNITION ENGINE - AN ADDITIVE FOR IGNITION-TIMING CONTROL -

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Abstract

Lean fuel/air mixtures with various fuel/fuel ratios between methane and n-butane were supplied to a premixed compression-ignition engine (i.e. homogeneous charge compression ignition engine, HCCI) with or without supplementary gaseous formaldehyde induction as an ignition controlling additive. In the no additive case the methane and butane function as the two fuels in the high/low-octane two-fuel premixed compression-ignition operation we proposed previously as another ignition control procedure. The formaldehyde addition to the methane/ butane/air mixtures has given the engine desired and stable ignition timings controllable by the amount of formaldehyde to be added, almost independent on the fuel/fuel ratios between methane and butane. The efficacy of formaldehyde has been confirmed as an ignition controlling medium for the piston-compression ignition of hydrocarbon/air mixtures.

Key Words: *Internal Combustion Engine, Ignition, Low-Temperature Flame, Preflame Reaction, Ignition Control, HCCI*

1. Introduction

The present obstacle to realize the premixed compression-ignition engine (HCCI) is the lack of effective ignition control procedure. We have proposed and confirmed the formaldehyde as an efficacious additive into the mixture to realize wide-range premixed compression-ignition operation of the natural gas engine (1). The main constituent of natural gas is methane, and the remainder are ethane, propane, butane and propylene. It is well known that the methane would not generate cool flame during its preflame period in the autoignition processes; quite different from the higher hydrocarbon fuels including propane, butane, gasoline and diesel oils (2). The most important intermediate during the preflame period up to the hot-flame establishment of the hydrocarbon fuels is the formaldehyde, which is closely related to the cool-flame appear- ance. It can be easily expected that the formaldehyde is effective in promoting ignition of the non-cool-flame generating fuel such as methane; the other way around about the cool-flame generating fuels.

The amount and combination of each component species in natural gas fuel, especially the ratio between propane and butane, change day by day, which results in the ignition-characteristics fluctuation of the engine fuel gases. The increase of butane content compared to propane would bring the engine to earlier ignition timings. Measures should be found out to eliminate the fluctuation of ignition. We propose herewith an ignition-control concept utilizing the gaseous formaldehyde as an additive to realize premixed compression-ignition engines and to maintain stabilized operation of spark-ignited natural gas engines.

2. Experimentals

A single cylinder diesel, Yanmar L60ADDP, four-stroke, air-cooled, 273 cm^3-displacement volume engine, was used to confirm the proposing concept. The combustion chamber was simplified to a pancake type. The compression ratio ε was 18 (real compression ratio: 14.8). A pressure transducer (Kyowa Electronic Instruments: PE-200K WS) and a needle-type high-speed electromagnetic sampling valve (Tsukasa: NW42) were installed on the cylinder head.

The engine was connected to an AC dynamometer to absorb the engine power output as well as to enable motoring operations without a break. The engine was operated under the WOT condition; the intake system had no throttle valve. The engine speed was 600 rev/min (10/s) during whole experiments. Cylinder head temperature was fixed at 80 °C.

Lean fuel/air mixtures with various fuel/fuel ratios between methane (octane rating: 120) and n-butane (octane rating: 94) were supplied to a single cylinder, premixed compression-ignition engine with or without supplementary gaseous formaldehyde induction as an ignition controlling additive. The n-butane represented the cool-flame generating fuels contained in natural gases. Fuel gases and formaldehyde were introduced continuously from the uppermost stream part of intake pipe as the gaseous state to obtain homogeneous mixtures. The formaldehyde adulterated into the intake air was a standard gas balanced or diluted by nitrogen or our own-make pure and nitrogen-diluted gases.

The in-cylinder gases were sampled once every ten-cycle interval with a valve opening period of 1.5 ms (equivalent to 5.4° CA at engine speed of 600 rpm). Container was connected via the valve and kept warm at 385 K. The sampled gasses were analyzed by gaschromatographs having TCD and FID detectors (GL Science: GC-390 DDTF, -390DDT) with a Porapak Q-S and Molecular Sieve 13X columns. The target species were CO, CO_2, HCHO, H_2O, H_2, O_2, 1-C_4H_8, C_2H_4, CH_4 and n-C_4H_{10}. The CO, CO_2 and HCHO gasses were deoxidized to methane by a catalytic converter and then detected by a FID.

3. Results and Discussion

3.1 Ignition-timing depending on high/low octane-rating two-fuel characteristics

Premixed piston-compression ignition operations using n-butane/methane/air mixtures are shown as pressure histories in Fig. 1, in which n-butane ratio to the total fuels is 0.359, 0.420 and 0.454 by volume under a fixed equivalence ratio ϕ of 0.52. The compression ratio ε was fixed to be 18.0. Total chemical energy retained in the mixtures are almost constant. Timings the hot-flame ignition can be achieved were 10.8, 2.0 and 0.8 degrees after top dead center (° aTDC) respectively. An increase of n-butane ratio to the total fuels brings about an advanced timing of hot-flame ignition. As a matter of course, the highest output torque was obtained in the 0.8° aTDC case. The nature of "high/low octane-rating two-fuel ignition-timing control" (3) for the premixed compression-ignition engine operations was revealed here again, though the difference of octane rating between methane and n-butane was not large.
The butane content lower than 0.35 could not lead to a reliable hot-flame appearance, associated with excessively retarded and unstable ignition timings. An 0.27 butane-content case is shown together in the figure. A wider range ignition timing and/or output torque control by the high/low octane-rating two-fuel system could be accomplished by using two fuels with a larger octane-rating difference between the two (4).

3.2 Formaldehyde addition to the mixtures with various fuel/fuel ratios

A few amount of formaldehyde was introduced to the above-mentioned n-butane/methane/air mixtures at the intake pipe portion. The formaldehyde content added to the whole fuel/air mixtures was 1 350 or 2 100 ppm. A relation between ignition timing and n-butane content in the total fuel is shown in Fig. 2. The pressure traces in these two cases are shown in Fig. 3 together with the traces of no addition cases. The timings hot-flame ignition would occur were around 5° and 3° aTDC independent of fuel/fuel ratio. The ignition timing is determined through the amount of formaldehyde added to the fuel/air mixture.

For the non-cool-flame generating methane n-butane mixed with it as a supplementary fuel acts as an intense ignition promoter, even though its octane rating is almost as high as the commercial gasoline. The ignition promoting effect of n-butane to the methane, however, would saturate at a certain extent. When the formaldehyde is introduced into the mixture the amount of formaldehyde added to the fuel/air mixture becomes a sole controlling factor to the ignition timing. It would be deserving special mention that the effect of formaldehyde addition is inhibitive for the mixtures with advanced hot-flame ignition tendency as contrasted with a promoting effect to the mixtures with retarded ignition tendency. It is also demonstrated that the operating range of premixed compression-ignition engine expands to both methane-abundant and butane-abundant directions.

3.3 Leaner mixture cases

In the 0.52 equivalence-ratio case the n-butane content, or fuel/fuel ratio, has poor controlling linearity. Another lean condition, a leaner equivalence ratio case with $\phi = 0.44$ was examined. No change was given on the compression ratio. The n-butane content was varied from 0.37 to 0.50. As a whole, leaner mixture supply has led retarded ignition timings beyond the top dead center.

Pressure traces in the formaldehyde adulterated case demonstrated the formaldehyde efficacy, in which the formaldehyde content added to the whole fuel/air mixtures was the same as the $\phi = 0.44$ case; 1 350 or 2 100 ppm. The ignition timings become controllable and are settled to a certain crank angle according to the amount of formaldehyde introduced into the mixture, even for the 0.31 butane-content one.

For the leaner mixture, ignition-timing controllability by the fuel/fuel ratio is improved having a higher linearity. Engine operating range is also expanded.

3.4 Chemical species histories to the hot-flame ignition

In-cylinder gas sampled consecutively up to the hot-flame occurrences under the compression ratio 18 were analyzed concerning both of a simple methane/butane/air mixture case and a formaldehyde adulterated case. The equivalence ratio of the mixture was fixed to be 0.52. The initial formaldehyde concentration introduced in the mixture was set to be 0 and 1 300 ppm. In-cylinder pressure and gas constituent histories of engine operation under the condition the butane content was 0.45 are shown in Fig. 4 as a typical example. The abscissa is the crank angle. Every concentration was plotted at the halfway timing of the whole valve opening period.

The starting of distinct heat release due to hot-flame occurrence could be recognized when compared to the pressure trace of air-only supplied trace. It is clearly shown that in the case with 1 300-ppm initial formaldehyde concentration the hot flame began at +6° CA and -1° CA near the TDC in the simple mixture case without formaldehyde addition. According to the raised formaldehyde concentration the hot-flame ignition timing is retarded due to the high butane content with an advanced ignition tendency.

The beginning of formaldehyde consumption was at +4° CA in the case with 1 300-ppm initial formaldehyde concentration and at the TDC in the simple mixture case. The earlier hot-flame occurrence is accompanied with the earlier start of formaldehyde consumption.

The carbon-monoxide concentration was always higher than that of carbon-dioxide before the ignition. The formaldehyde generated from the simple mixture grew monotonously up to the hot flame occurrence. The timing of maximum carbon-monoxide concentration was not far away from the timing the carbon dioxide generated most rapidly. The carbon-monoxide concentration seems to be closely related to the heat release rate of hot-flame explosion.

A piston compression of a simple charge of methane/butane and air contained no intake formaldehyde addition showed a gradual formaldehyde generation during the preflame period and slight consumption at the final stage before the hot-flame occurrence. In the formaldehyde adulterated case the formaldehyde concentration shows a slight rise followed by prompt decrease at the final stage of the ignition delay period; so-called blue-flame period, but seemingly stable during almost the whole induction period up to the ignition.

Methane consumption is very low during the whole induction period. Concerning the n-butane consumption, degenerate nature can be recognized only in the no addition case.

The effect of formaldehyde added into the methane/butane/air mixture leading to the ignition would be an inhibitive event for the cool-flame generating constituent and a promoting event of the preflame reaction of the non-cool-flame generating constituent in the fuel.

4. Concluding Remarks

Methane is the main constituent of natural gas, and the remainder is ethane, propane, butane and others. The former is a non-cool-flame generating fuel as contrasted with cool-flame generating remainders.

- Cool-flame generating constituent of natural gas will act as an ignition promoter for the main constituent, methane. The nature of high/low octane-rating two-fuel ignition-timing control for the premixed compression-ignition engine operation is revealed for the fluctuation of natural gas constituents. An increase of cool-flame generating remainder ratio brings about an advanced timing of hot-flame ignition. The ignition promoting effect to the methane, however, would saturate at a certain extent.

A small amount of formaldehyde added into the methane/ butane/air mixtures has given the engine desired and stable ignition timings according to the amount of formaldehyde added, almost independent on the fuel/fuel ratios between methane and butane.

- Amount of formaldehyde added to the fuel/air mixture becomes a sole controlling factor to the ignition timing. The effect of formaldehyde addition is inhibitive for the mixtures with advanced hot-flame ignition timings as contrasted with a promoting effect to the mixtures with retarded ignition timings.

- Troubles due to the day-by-day ignition-characteristic fluctuation of the engine fuel gases can be eliminated by using a small amount of formaldehyde for the premixed compression-ignition and spark-ignited natural gas engines.
- Operating range of premixed compression-ignition engine expands to both methane-abundant and butane-abundant directions.

Formaldehyde is efficacious as an ignition controlling medium for the hydrocarbon/air mixtures in engine cylinders. The effect of formaldehyde leading to the ignition would be an inhibitive event for the cool-flame generating constituent and a promoting event of the preflame reaction of the non-cool-flame generating constituent in the fuel gasses.

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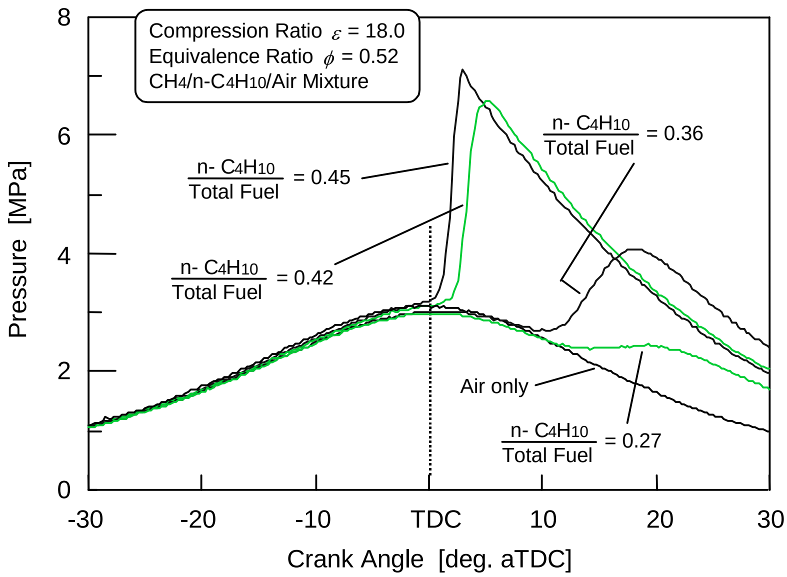

Fig. 1. *Pressure traces of methane/butane/air ignition at an equivalence ratio $\phi = 0.52$ with various fuel/fuel ratios. Compression ratio $\varepsilon = 18$.*

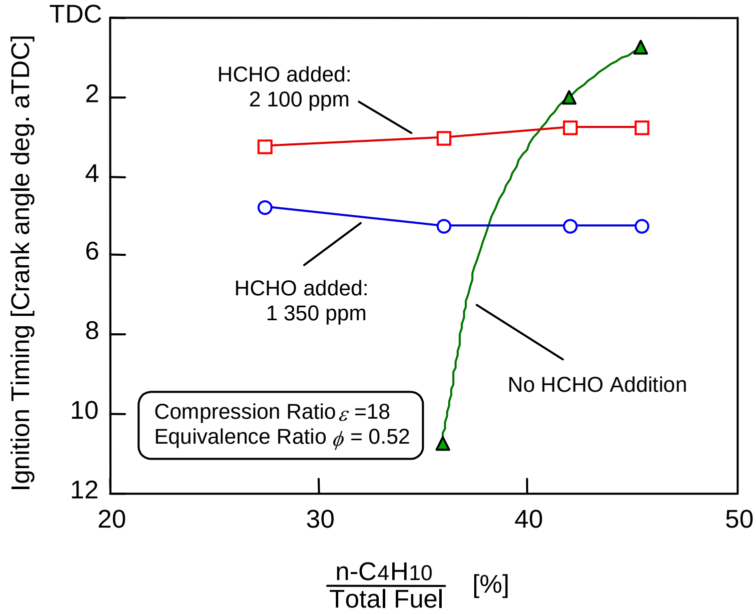

Fig. 2. *Effect of HCHO addition on the ignition timing stabilization and fuel constituent fluctuation. Compression Ratio $\varepsilon = 18$.*

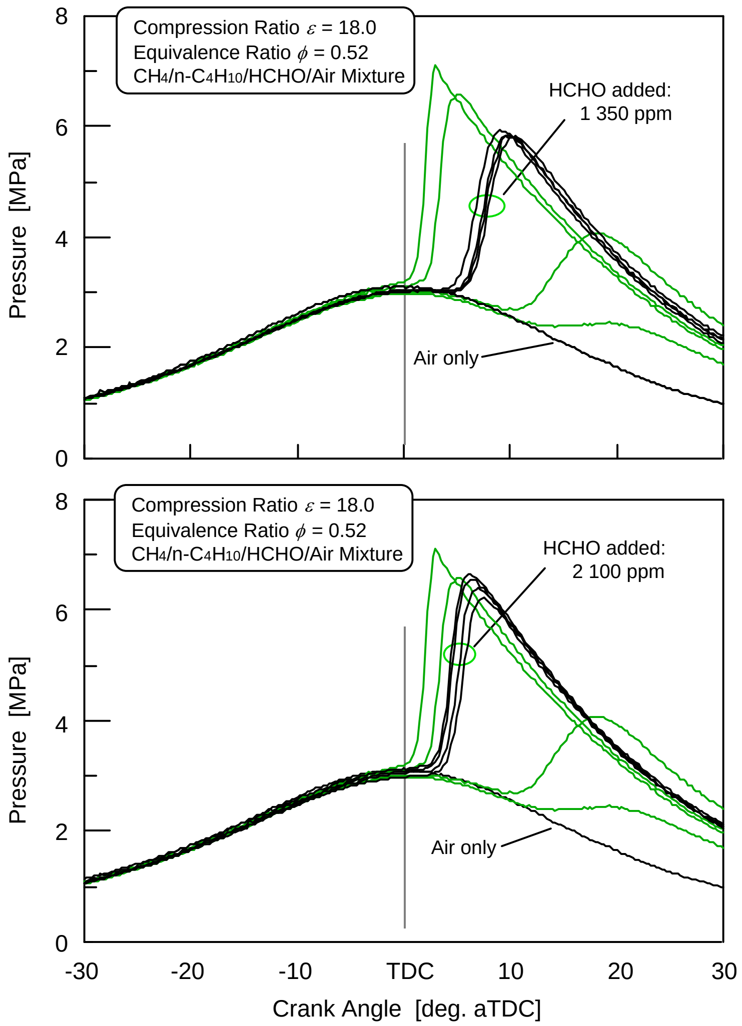

Fig. 3. *Pressure traces of methane/butane/air ignition when HCHO is added into the mixture having various fuel/fuel ratios and a fixed equivalence ratio $\phi = 0.52$. Compression ratio $\varepsilon = 18$.*

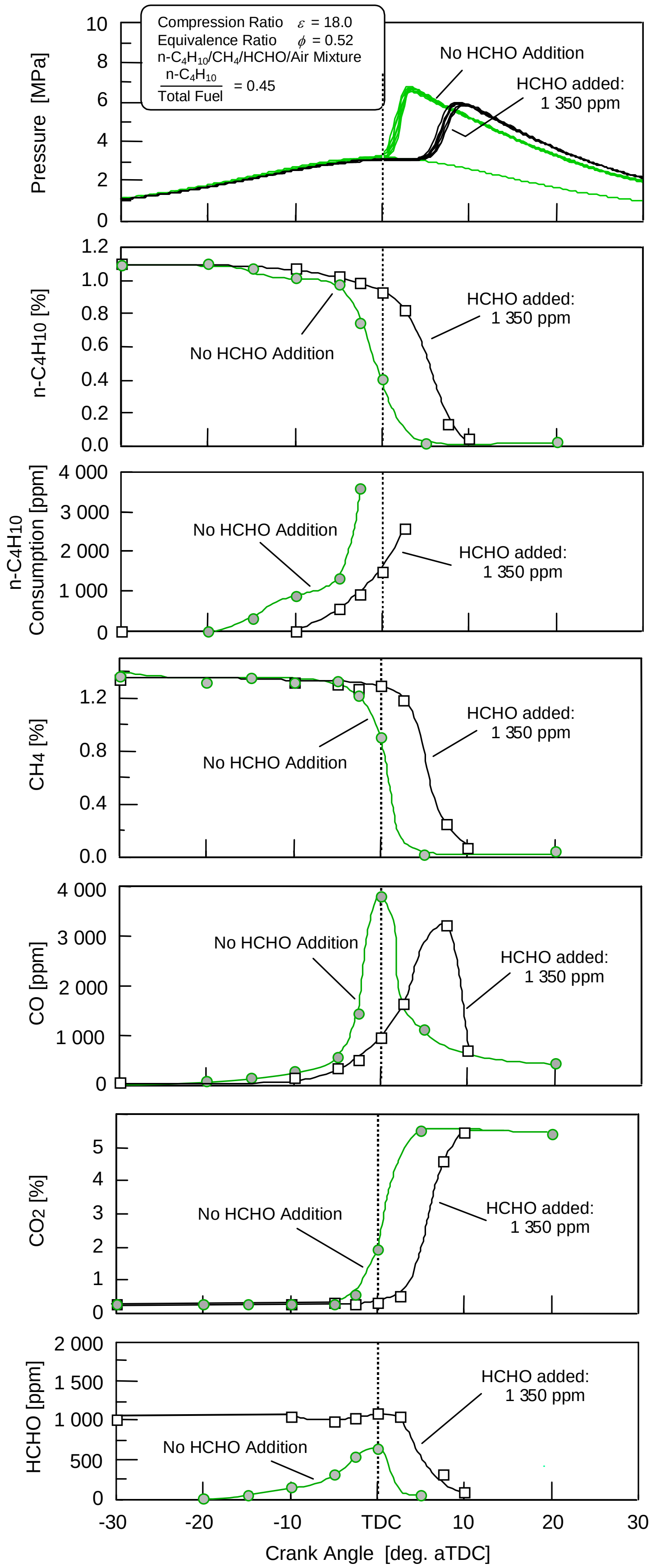

Fig. 4. *Species concentration histories in 0.45-butane-content methane/butane/HCHO/air ignition at an equivalence ratio $\phi = 0.52$ when the intake HCHO concentration 1350 ppm, associated with pressure traces. Compression ratio $\varepsilon = 18$.*