Combustion Mechanism Analysis with In-chamber Gas Composition Measurements in a Premixed Lean Compression Ignition Engine

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ABSTRACT

The in-chamber and exhaust gases from a premixed lean compression ignition engine were evaluated with high-speed direct gas sampling and gas chromatography. The results showed that in premixed lean CI combustion the in-chamber concentrations of THC and CO were always much higher than in conventional diesel combustion and remained nearly constant after the main part of the heat release was complete. The THC near the piston cavity wall was much higher than at the center of the combustion chamber and near the cylinder head. Deposition of fuel on the piston face is believed to be the main reason for higher THC emissions from premixed lean CI combustion. The experiments with the model fuels showed that during combustion the relative fractional amounts of hydrocarbon components with lower boiling points decreased more than higher boiling point components, while there was little difference in the relative fractional amounts based on component ignitability.

INTRODUCTION

A premixed lean compression ignition engine can realize extremely low NOx and particulate emissions than a conventional diesel engine though at the expense of much higher unburned THC and CO (1)-(3). Other disadvantages of the premixed lean CI engine arise in the control of ignition timing and operation at lower excess air ratios without knocking. Analysis of the evolution of the in-chamber gas composition, which has been reported for ordinary diesel engines (4), (5), is expected to point to solutions to these difficulties and explicate the combustion mechanisms of the premixed lean CI engine.

This research utilized high-speed direct gas sampling and gas chromatography to measure in-chamber and exhaust gases from a premixed lean CI engine. The in-chamber gas was sampled at several crank angles in the range from prior to the ignition in the compression stroke to late in the expansion stroke. The investigation covered three excess air ratios: the knocking limit, a stable region, and the misfiring limit. A poppet type valve was used to collect larger amounts of gas, and a needle type nozzle providing high spatial resolution was used to investigate the influence of sampling position. With the needle valve, gas samples were taken at three positions: near the cylinder head, on the side of the combustion chamber, and near the bottom of the piston cavity. Tests were conducted with ordinary diesel fuel and three model fuels with known hydrocarbon contents. The model fuel compositions were chosen to allow independent analysis of the effects of component molecular structure, ignitability, and boiling point.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were conducted on a single cylinder, 4-stroke cycle, DI diesel engine with specifications as in Table 1. The compression ratio was reduced from 18.0 to 12.0 by using a piston with a larger volume, shallow, dish-shaped cavity (shown in Fig. 1) to realize reasonable ignition for a premixed lean CI engine. A common rail type fuel injection system enabled a wide range of changes in the fuel injection timing. The operating conditions were set at an engine speed of 1100 rpm, and a coolant temperature of 80°C. The three excess air ratios, the knocking limit at excess air ratio, at \( \lambda = 3.0 \), a stable region at \( \lambda = 4.0 \), and the misfiring limit at \( \lambda = 5.0 \), were investigated although most experiments were performed at \( \lambda = 4.0 \). Fuel injection timing for premixed lean CI combustion was set at 95°C BTDC except for \( \lambda = 3.0 \) where it was 145°C BTDC, while it was at 10°C BTDC for ordinary diesel combustion.

Conventional diesel fuel (JIS No.2) and three model fuels with known hydrocarbon contents were used. The components of the model fuels and their properties are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Details of the tested engine</th>
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<td><strong>Type</strong></td>
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<td>Bore × stroke</td>
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in Table 2. Model fuel A has 51 vol % normal paraffin (mixture of C₁₃ to C₁₆) as the base component and 7 vol % of each of seven different types of pure hydrocarbons, allowing for a comparison of the effect of the molecular structure of the fuel components. Model fuel B consists of a 50/50 mixture of n-tridecane and tetraline, and was chosen to compare the influence of the ignitability of the fuel components. Model fuel C, consisting of three normal paraffin hydrocarbons with different carbon numbers (C₁₀, C₁₀, and C₁₁), demonstrates the effect of fuel component boiling point.

A high-speed electromagnetic valve sampled the in-chamber gas at the position shown in Fig. 1. The fuel type was used primarily while a needle type nozzle was used only for high spatial resolution to investigate the influence of sampling position. The sampling duration was about 10°C for both valves and the center of the sampling period was defined as the sampling time. The poppet type valve can collect a larger quantity of gas, about 26 cm³N at the experimental condition when the sampling timing was set near top dead center. The collected amount with the needle valve at the same conditions was about 13 cm³N. To position the sampling point when the needle valve was used, a stainless steel tube (φ2 mm) was attached at the valve inlet as shown in Fig. 2. The syringe carrying the sampled gas from the outlet of the sampling valve was heated to prevent condensation of higher distillate components. Gas chromatography included a flame ionization detector (FID) for hydrocarbon components and a non-dispersive infrared detector (NDIR) for CO.

**EXPERIMENTAL RESULTS AND DISCUSSION**

**Combustion and Emissions in the Tested Premixed Lean CI Engine**

Before the in-chamber gas was analyzed, the performance and exhaust gas emissions from the premixed lean CI combustion of ordinary diesel fuel in the tested engine was investigated and compared with the conventional diesel combustion as shown in Fig. 3. Extremely low NOx and smokeless operation without significant deterioration in BSEC (brake specific energy consumption) can be realized with the premixed lean CI combustion while CO and THC emissions are, unfortunately, much higher than with conventional diesel combustion. The maximum BMEP is limited by knocking for premixed lean CI combustion at BMEP 0.3 MPa where the excess air ratio, λ, is 3.0. At the opposite extreme, idling operation (λ > 5) is impossible because of misfiring.

Fig. 4 shows the results of gas sampling and analyses of indicator diagrams for premixed lean CI combustion and conventional diesel combustion at λ=4 with model fuel A. Preliminary combustion can be observed at 15°C BTDC on the rate of heat release (ROHR) diagram for the premixed lean CI combustion. The in-chamber concentrations of THC and CO in the premixed lean CI combustion is always much higher than conventional combustion even though the nonuniformity of conventional combustion may lead to a lean mixture at the sampling position. The THC and CO in the premixed lean CI combustion is constant or slightly increasing after the main part of the heat release is completed at 20°C ATDC when the mean gas temperature in the combustion chamber is high enough for oxidation of these species to occur. This unexpected result suggests that a significant amount of fuel is deposited on the piston surfaces during compression and it evaporates during the expansion and exhaust strokes. Apparently, the magnitude of THC addition due to evaporation from the piston surfaces, in the expansion stroke, is nearly equal to or slightly greater than the magnitude of THC oxidation in the bulk gases. Evidence of the magnitude of fuel believed to be deposited on the combustion chamber surfaces can be seen by comparing the measured fuel concentration prior to the start of ignition with the ideal concentration assuming a uniform mixture. If all injected fuel were perfectly premixed with intake air, the THC concentration before ignition would be more than 10,000 ppmC. However, the measured THC at 40°C BTDC
Fig. 3 Exhaust emissions and BSEC with ordinary diesel fuel in the premixed lean CI and in conventional diesel operation (before start of preliminary combustion) was less than 2000 ppm C.

Fig. 4 THC and CO concentrations in the in-chamber and exhaust gases, pressure, mean gas temperature, and rate of heat release diagrams in premixed lean CI and conventional diesel combustion with model fuel A

Influence of Excess Air Ratio on Gas Compositions in the In-Chamber and Exhaust Gases

Fig. 5 shows the fraction of hydrocarbon components in the in-chamber and exhaust gases for the premixed lean CI combustion under the same conditions as in Fig. 4. In the figure, the original fuel components are arranged in order of decreasing cetane number. There are no significant changes in the relative fractions of original components in the in-chamber and exhaust gases while the proportion of cracked components increases as they are formed during the main combustion. However, the fraction of xylene, which has the lowest boiling point, is much smaller than the others throughout the measured range. The influence of the boiling temperatures on the in-chamber hydrocarbon fractions will be discussed in detail later.

Fig. 5 Hydrocarbon fractions in the in-chamber and exhaust gases in the premixed lean CI combustion with model fuel A (\( \lambda = 4 \))

0.3 MPa (where knocking starts to occur), \( \lambda = 4 \) corresponds to BMEP = 0.2 MPa, and \( \lambda = 5 \) corresponds to BMEP = 0.05 MPa, which is the misfiring limit. Preliminary combustion with a small heat release can be seen before the main combustion for all three excess air ratios. Both the preliminary and main combustion at \( \lambda = 3 \) have greater heat release and occur
earlier than for the other excess air ratios. There is little difference between $\lambda = 4$ and 5 in the pressure and ROHR diagrams, while the mean gas temperature after the main combustion for $\lambda = 5$ is significantly lower than for $\lambda = 4$.

Fig. 7 shows the evolution of the in-chamber concentrations of CO and THC in premixed lean CI combustion for the same three excess air ratios shown in Fig. 6. Operation at the misfiring limit, $\lambda = 5$, yielded a much shallower decline in THC as well as more CO formation during the main combustion than with the smaller excess air ratios. Like the results for model fuel A (Fig. 4), the in-chamber concentrations of THC and CO for all three excess air ratios are nearly constant after the main part of the heat release is complete. However, both the THC and CO concentrations with ordinary diesel fuel are much higher than with model fuel A throughout the measured crank angle range.

Fig. 8 shows the fraction of hydrocarbon components under the same conditions as in Figs. 6 and 7. The components with carbon numbers less than 12 consist of mainly cracked components. At the knocking limit, $\lambda = 3$, the cracked component fractions from the original fuel is much higher than for $\lambda = 4$ and 5 even at 40$^\circ$CA BTDC, which is prior to the start of the preliminary combustion. At $\lambda = 4$ and 5, component fractions with carbon numbers in the range 13 to 15, components of original fuel, were dominant.

**In-Chamber Concentrations of CO and THC at Different Sampling Positions**

Fig. 9 shows the in-chamber concentrations of CO and THC at different sampling positions in premixed lean CI combustion with ordinary diesel fuel. The needle type sampling valve was used here to extract spatially distinct gas samples located near the cylinder head, at the center of the combustion chamber, and near the bottom of the piston cavity for the piston at TDC. The THC concentration near the piston surface was much higher than the concentrations at the other two locations. This result suggests that the deposition of fuel on the face of the piston cavity is considerable and could be the main reason for the higher THC emissions with premixed lean CI combustion.

**Influence of Ignitability of Fuel Components on the In-Chamber Gas Composition**

Both THC and CO concentrations with ordinary diesel fuel (Fig. 7) are much higher than those with model fuel A (Fig. 4) throughout the measured range. This may be caused by components of the ordinary diesel fuel, such as aromatics, with low ignitability or high distillation temperatures.
Model fuel B, with 50 vol % of each n-tridecane and tetraline, was used to investigate the influence of the ignitability of fuel components on the in-chamber gas compositions in the premixed lean CI engine. Fig. 10 shows the results of gas sampling and analyses of indicator diagrams with premixed lean CI combustion with model fuel B. Results similar to model fuel A were obtained for ROHR and in-chamber concentrations of THC and CO while the concentrations of CO and THC in the later expansion stroke and exhaust manifold are lower than for model fuel A which contains 51 vol % n-paraffin with higher distillation temperature.

Fig. 11 shows the gas chromatographic analysis of the hydrocarbons in the in-chamber and exhaust gases with model fuel B. The fraction of tetraline, with lower ignitability, decreases throughout the preliminary combustion and main combustion and remains nearly constant until 100°CA ATDC in the expansion stroke. The fraction of n-tridecane, with higher ignitability, experiences a slight increase relative to total hydrocarbons during preliminary combustion and remains almost unchanged even as it exits the cylinder as exhaust. This unexpected result may be caused by the lower boiling temperature of tetraline (207°C) compared with n-tridecane (234°C). Nevertheless, there appears to be no significant effect of the ignitability of fuel components on THC in the premixed lean CI combustion.

**Influence of Distillation Temperatures of Fuel Components on the In-Chamber Gas Composition**

Fig. 12 shows the results of gas sampling and analyses of indicator diagrams for the premixed lean CI combustion with model fuel C. Results similar to those with model fuels A and B were obtained for the ROHR and in-chamber THC and CO concentrations.

Fig. 13 shows the gas chromatographic analysis of the hydrocarbons in the in-chamber and exhaust gases with model fuel C. The fractions of n-heptane and n-decane disappeared during the combustion phase while the proportion of
1. The deposition of fuel on the piston face is significant and could be the main source of higher THC emissions from the premixed lean CI combustion.

2. The concentrations of THC and CO in the combustion chamber of the premixed lean CI engine remain much higher than in a conventional diesel engine, and are nearly constant after completion of the main part of the heat release even though the mean gas temperature in the combustion chamber is high enough for oxidation of these components.

3. At the misfiring limit the decrease in THC during combustion is much smaller and CO formation is greater than at other excess air ratios.

4. At the knocking limit the fraction of hydrocarbon components mainly cracked from the original fuel is much higher, while the original fuel components are dominant at other higher excess air ratios.

5. The THC concentration near the piston face was much higher than the concentrations at the center of the combustion chamber and near the cylinder head. This indicates significant fuel deposition on the piston face followed by evaporation after the main part of heat release.

6. There is no noticeable effect of the ignitability of fuel components on the hydrocarbon emissions in the premixed lean combustion.

7. The fuel deposited on piston surfaces consisted mainly of high distillation temperature components. Fuels without high distillation temperature components would reduce THC emissions from premixed lean CI combustion.

ACKNOWLEDGMENTS

The authors wish to express their sincere appreciation to Mr. Kevin R. Sholes, a graduate student at University of Wisconsin for his advice, to Mr. Atsushi Sakai and Mr. Masahiro Minami, graduate students at Hokkaido University, and to Mr. Hitoshi Kogure and Mr. Taku Ishidoya, undergraduate students at Hokkaido Institute of Technology, for their cooperation in the experiments.

REFERENCES


