Analysis of OH Radical Emission Intensity during Autoignition in a 2-Stroke SI Engine

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ABSTRACT

This research focused on the light emission behavior of the OH radical (characteristic spectrum of 306.4 nm) that plays a key role in combustion reactions, in order to investigate the influence of the residual gas on autoignition. The test engine used was a 2-stroke, air-cooled engine fitted with an exhaust pressure control valve in the exhaust manifold. Raising the exhaust pressure forcibly recirculated more exhaust gas internally. Emission measurements were made under three conditions: normal combustion without any forced application of internal EGR, forced application of light internal EGR and forced application of heavy EGR. When a certain level of internal EGR is forcibly applied, the temperature of the unburned end gas is raised on account of heat transfer from the hot residual gas and also due to compression by piston motion. As a result, the unburned end gas becomes active and autoignition tends to occur.

INTRODUCTION

Global warming is an issue that has been much discussed internationally in recent years. Growing concern about environmental issues has placed internal combustion engines in a very difficult position. This is especially true for 2-stroke engines which do not operate stably under light loads and also tend to emit a large quantity of unburned hydrocarbons (HCs) [1]. However, depending on the engine speed and the level of internal exhaust gas recirculation (EGR) that is applied, a process leading to autoignited combustion can be obtained. It has been reported that this combustion process allows stable engine operation with a low level of unburned HC emissions [2]. This type of combustion, referred to as active thermo-atmosphere combustion (ATAC) [2] or activated radical combustion (ARC) [3], is thought to be bulk state combustion resulting from autoignition at multiple locations rather than from flame propagation [4-6]. There are still many aspects, however, of the autoignition mechanism which are not clearly understood.

The purpose of this research was to investigate the influence of the residual gas on autoignition. Attention was focused on the light emission behavior of the OH radical (characteristic spectrum of 306.4 nm), which plays an important role in the elemental reaction process of hydrocarbon fuels. An exhaust pressure control valve was installed in the exhaust manifold of the test engine in order to forcibly apply internal EGR by raising the exhaust pressure. The emission behavior of the OH radical was investigated under the conditions of normal combustion without any forced application of internal EGR, forced application of light internal EGR and forced application of heavy internal EGR.

EXPERIMENTAL EQUIPMENT AND METHOD

The specifications of the test engine are given in Table 1, and the exhaust pressure conditions under which experimental measurements were made are shown in Table 2. Figure 1 is a schematic of the test equipment, and the measurement positions and scavenging ports are shown schematically in Fig. 2.

The emission behavior of the OH radical was measured by means of quartz observation window holders fitted to the end zone of the combustion chamber at two locations, one on the exhaust port side and the other on the intake port side. The flame light extracted through these observation windows was introduced into polychromators [7] via optical fiber.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Specification of test engine</th>
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<tr>
<td>2-Stroke SI Engine</td>
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<tr>
<td>Type of Scavenging System</td>
<td>Schnürle</td>
</tr>
<tr>
<td>Bore × Stroke</td>
<td>72 × 60 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>244 cm³</td>
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<tr>
<td>Effective Compression Ratio</td>
<td>8.0:1</td>
</tr>
<tr>
<td>Geometrical Compression Ratio</td>
<td>11.0:1</td>
</tr>
<tr>
<td>Ignition Timing</td>
<td>20 deg. BTDC/2000 rpm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Exhaust pressure conditions</th>
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<tbody>
<tr>
<td>Conditions</td>
<td>Exhaust Pressure (approximately)</td>
</tr>
<tr>
<td>A (Normal Combustion)</td>
<td>101.8 (Atmospheric Pressure) +1.7 [kPa]</td>
</tr>
<tr>
<td>B (Combustion with Light EGR)</td>
<td>101.7 (Atmospheric Pressure) +5.8 [kPa]</td>
</tr>
<tr>
<td>C (Combustion with Heavy EGR)</td>
<td>101.7 (Atmospheric Pressure) +8.1 [kPa]</td>
</tr>
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</table>
EXPERIMENTAL RESULTS AND DISCUSSION

Measured Waveforms

Figure 3 shows typical examples of the waveforms measured under Condition A (normal combustion). From the top, the figures show the knocking intensity waveform, cylinder pressure waveform, and the emission intensity waveforms measured on the exhaust and intake port sides at a wavelength of 306.4 nm, thought to correspond to the characteristic spectrum of the OH radical. The spark plug washer temperature \( T_{wp} \) was 615 K.

The cylinder pressure rose gradually to a maximum pressure of approximately 2.0 MPa, after which it gradually declined. On the exhaust port side, OH radical emission began at a crank angle (CA) of approximately 6.7 deg. after top dead center (ATDC), while on the intake port side, it began at a crank angle of approximately 19.9 deg. ATDC. The onset of OH radical emission on the intake port side thus occurred approximately 13 CA deg. later than on the exhaust port side. This difference is attributed to in-cylinder gas flow from the intake port side to the exhaust port side on account of the Schnürle scavenging system used in the test engine. As a result, it is assumed that flame propagation to the intake port side took place relatively later than to the exhaust port side. The interval from the onset of OH radical emission to the crank angle showing the maximum emission intensity \( b_0 \) was approximately 6.5 CA deg. in duration on the exhaust port side and approximately 13.3 CA deg. on the intake port side. The maximum emission intensity \( E_{\text{max}} \) of the OH radical was approximately 3.0 V and 3.7 V on the exhaust and intake port sides, respectively.

In Fig. 4, the waveforms measured under Conditions B
and C (combustion with light and heavy internal EGR, respectively) are superposed on those shown in Fig. 3 for Condition A.

The spark plug washer temperature ($T_{wp}$) measured under Condition B (combustion with light internal EGR) was 609 K. The interval from the onset of OH radical emission to the crank angle showing the maximum emission intensity ($\theta_{O_{2},\text{max}}$) was approximately 3.2 CA deg. in duration on the exhaust port side and approximately 6.0 CA deg. on the intake port side. The maximum emission intensity ($E_{\text{max}}$) of the OH radical was approximately 5.4 V and 4.0 V on the exhaust and intake port sides, respectively. The cylinder pressure waveform under Condition B rises at a crank angle of approximately 16.4 deg. ATDC, an increase that is not observed in the cylinder pressure waveform for Condition A.

The spark plug washer temperature ($T_{wp}$) measured under Condition C (combustion with heavy internal EGR) was 598 K. The interval from the onset of OH radical emission to the crank angle showing the maximum emission intensity ($\theta_{O_{2},\text{max}}$) was approximately 3.1 CA deg. in duration on the exhaust port side and approximately 4.6 CA deg. on the intake port side. The maximum emission intensity ($E_{\text{max}}$) of the OH radical on the exhaust and intake port sides was approximately 8.1 V and 7.8 V, respectively. The cylinder pressure waveform measured under Condition C begins to rise at a crank angle of 9.0 deg. ATDC, and the increase is steeper than that seen for Condition B.

Forcibly increasing the application of internal EGR had the effect of shortening the interval from the onset of OH radical emission to the crank angle showing the maximum emission intensity ($\theta_{O_{2},\text{max}}$) and of increasing the maximum emission intensity ($E_{\text{max}}$). Applying heavier internal EGR presumably increases the quantity of residual gas, and the unburned end gas is affected by heat transfer from the hot residual gas. Both Conditions B and C showed higher cylinder pressures than Condition A during the compression stroke from a crank angle of 40 deg. BTDC to top dead center. Since the test engine was operated under a condition of a nearly constant intake air quantity, the greater amount of residual gas present under Conditions B and C than under Condition A resulted in a somewhat higher boost pressure, which would account for the higher cylinder pressure. It is thought that the temperature of the unburned end gas is raised because of heat transfer from the residual gas and also due to compression by piston motion. As a result, the unburned end gas becomes active, creating a state that is conducive to the occurrence of autoignition.

The onset of OH radical emission on the exhaust port side occurred at a later crank angle under Conditions B and C than under Condition A. On the intake port side, the onset of OH radical emission occurred at an earlier crank angle under Conditions B and C than under Condition A.

Fig. 5 shows typical results obtained under Condition C (combustion with heavy internal EGR). The spark plug washer temperature ($T_{wp}$) recorded here was 665 K, indicating
Analysis

As observed in Fig. 4, increasing the application of internal EGR shortened the interval from the onset of OH radical emission to the crank angle showing the maximum emission intensity ($\theta_{max}$). This indicates that the OH radical increased in quantity in a short period of time. The rate of increase in the OH radical emission intensity was defined as $dE/d\theta$ [V/deg.], and is calculated by dividing the maximum emission intensity ($E_{max}$) of the OH radical by the interval from the onset of OH radical emission to the crank angle showing the maximum emission intensity ($\theta_{max}$).

In Fig. 4, the rates of increase in the OH radical emission intensity $dE/d\theta$ [V/deg.] on the exhaust and intake port sides under Conditions B and C were larger than those seen for Condition A (normal combustion). The respective values were 1.697 and 0.660 for Condition B, 2.600 and 1.696 for Condition C and 0.463 and 0.281 for Condition A. Cycles in which the knocking intensity was 0.04 MPa or higher were defined as knocking cycles. The AI cycles were defined on the basis of the following conditions: the knocking intensity was less than 0.4 MPa, pressure rises were observed in the pressure waveforms under Conditions B and C in Fig. 4 but not in the pressure waveform of Condition A, the rate of increase in the OH radical emission intensity $dE/d\theta$ [V/deg.] under Conditions B and C was larger than that observed for Condition A, and, accordingly, it was presumed that autoignition occurred.

In Figs. 6-8, the circles (○, ⊙), and triangles (△, △) represent cycles which were not AI cycles and no knocking pressure oscillations were observed. The open symbols (○, △) indicate AI cycles, and the closed symbols indicate cycles in which knocking pressure oscillations were observed. The data plots in the graphs in Figs. 6-8 indicate the mean values of the results measured in five cycles in an identical

\[\text{Fig. 5 Measured waveforms for knocking under Condition C} \]

(combustion with heavy internal EGR)

an overheated cylinder head. The pressure waveform rises sharply from a crank angle of approximately 3.5 deg. ATDC and shows evidence of knocking pressure oscillations. The emission intensity waveforms measured on the intake and exhaust port sides show pulsation. The frequency of the knocking pressure oscillations and that of the radical on both the exhaust and intake port sides were approximately 8.0 kHz. The peaks and troughs in the emission intensity waveforms on the two sides show a phase difference of 180 deg. Emission intensity is known to be dependent on the product of the concentration of the radicals in an excited state multiplied by the probability of their transition to normal state [8]. The radical concentration is affected by pressure, and the transition probability is influenced by temperature. Pressure fluctuations due to the oscillations caused by knocking produce localized changes in the combustion gas concentration, which affect the emission intensities of the radicals. This is thought to explain why the emission intensity waveforms show pulsation at the same frequency as the knocking pressure oscillations. Because the knocking pressure waves travel back and forth across the cylinder, reciprocal pressure behavior is seen on the intake and exhaust port sides [9-11]. This is believed to account for the 180 deg. phase difference seen in the emission intensities on the two sides of the combustion chamber.

\[\text{Fig. 6 Rate of increase in OH radical vs. spark plug washer temperature under Condition A} \]
Figure 7 shows the rate of increase in the OH radical emission intensity (dE/dθ) under Condition B (normal combustion) as a function of the spark plug washer temperature (Twp). When comparisons are made of the same temperature regions, it is seen that the rate of increase in the OH radical emission intensity was higher on the exhaust port side than on the intake port side. Since the intake port wall was cooled by the incoming fresh air, whereas the exhaust port wall was heated by the hot exhaust gas, it can be presumed that the latter had a higher temperature than the former. It can be inferred, therefore, that the OH radical would show a higher rate of increase on the exhaust port side than on the intake port side because of heat transfer from the exhaust port wall. Under Condition A (normal combustion) with the EGR control valve fully opened, a progression to autoignition and knocking operation did not occur even though the cylinder head temperature increased.

Figure 8 shows the rate of increase in the OH radical emission intensity (dE/dθ) under Condition C (combustion with heavy EGR) as a function of the spark plug washer temperature (Twp). It is seen in Fig. 8 that the rate of increase in the OH radical emission intensity (dE/dθ) on both the intake and exhaust port sides tends to rise with an increasing spark plug washer temperature (Twp). Once the spark plug washer temperature (Twp) exceeds approximately 570 K, the cycles become AI cycles like those seen in Fig. 4 for Conditions B and C. Knocking pressure oscillations begin to appear once the spark plug washer temperature (Twp) reaches approximately 630 K. The rates of increase in the OH radical emission intensity (dE/dθ) are virtually identical on the intake and exhaust port sides under Condition C (combustion with heavy EGR), compared with the data seen in Fig. 6 for Condition A (normal combustion) and the results in Fig. 7 for Condition B (combustion with light EGR). Because of the high exhaust pressure, a larger quantity of residual gas was present under Condition C than in the case of the other two conditions. Accordingly, the residual gas temperature near the measurement position on the intake port side would not be lowered very much by incoming fresh air under Condition C compared with the decrease that occurred under Condition B. Consequently, the unburned gas on the intake port side under Condition C was more active than that under Conditions A and B because of the heat it received from the residual gas. This is presumed to be the reason why the rate of increase in the OH radical emission intensity showed nearly the same values on both the intake and exhaust port sides under Condition C. It is also thought that the residual gas in the vicinity of the measurement position on the intake port side was cooled by incoming fresh air, rendering the residual gas components inactive. This is thought to explain why the rate of increase in OH radical emission intensity (dE/dθ) was lower on the intake port side than on the exhaust port side.
temperature increased as the spark plug washer temperature rose. When the quantity of residual gas was approximately equal to the amount present under Condition C, the unburned end gas underwent autoignition due to heat transfer from the residual gas, and knocking pressure oscillations began to appear after the combustion chamber inner wall temperature rose above 630 K.

CONCLUSIONS

The emission intensity of the OH radical was measured using a 2-stroke, air-cooled engine equipped with a Schnurle scavenging system. Emission measurements were made under three types of conditions, normal combustion without any forced application of internal EGR, forced application of light internal EGR and forced application of heavy internal EGR. The measured results made the following points clear.

1. With the forced application of a certain level of EGR, heat is transferred from the residual gas to the unburned end gas and the temperature of the latter is also raised due to compression by piston motion. As a result, the unburned end gas becomes active and a state conducive to the occurrence of autoignition is created.
2. Forced application of internal EGR causes a progression to AI cycles once the spark plug washer temperature exceeds 570 K.
3. The application of internal EGR, equal in amount to that applied under Condition C in this work, induces a progression from AI cycles to knocking cycles as the combustion chamber inner wall temperature continues to rise.
4. The radical emission intensifies on both sides of the combustion chamber fluctuated at the same frequency as that of the knocking pressure oscillations. A phase difference of 180 deg. was observed between the intake and exhaust port side.

REFERENCES