

A Study on the Effect of Zn- and Mo-Based Engine Oil Additives on Abnormal SI Engine Combustion using In-Cylinder Combustion Visualization

Norikuni Hayakawa, Kenta Miura, Tomomi Miyasaka,
Takashi Ishino, Akira Iijima, and Hideo Shoji
Nihon University Graduate School

Kazushi Tamura, Toshimasa Utaka, and Hideki Kamano
Idemitsu Kosan Co. Ltd.

ABSTRACT

Spontaneous low-speed pre-ignition, strong knock and other abnormal combustion events that occur in supercharged direct-injection engines are viewed as serious issues. The effects of the engine oil and the components of engine oil additives have been pointed out as one cause of such abnormal combustion. However, the mechanisms involved have yet to be elucidated, and it is unclear how the individual components of engine oil additives influence autoignition.

This study investigated the effect on autoignition of boundary lubricant additives that are mixed into the engine oil for the purpose of forming a lubricant film on metal surfaces. A high-speed camera was used to photograph and visualize combustion through an optical access window provided in the combustion chamber of the four-stroke naturally aspirated side-valve test engine. Spectroscopic measurements were also made simultaneously to investigate the characteristics of abnormal combustion in detail. We mixed Zinc additive into primary reference fuel (PRF50) at zinc concentration of 115 ppm, 570 ppm and 800 ppm. In addition, we mixed Molybdenum additive into PRF 50 at molybdenum concentration of 140 ppm, 700 ppm and 980 ppm. Combustion experiments were conducted in this condition.

The experimental results revealed that both the Zinc and Molybdenum additives had little effect on abnormal combustion.

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INTRODUCTION

Various environmental issues make it necessary today to improve the efficiency of internal combustion engines. Supercharged and downsized engines have attracted widespread interest as one technical approach for accomplishing that. Supercharging increases the mean effective pressure of the engine, making it possible to attain higher specific power even in the region of relatively low engine speeds. However, low-speed and high-load engine operating conditions tend to cause abnormal combustion. Consequently, it is well known that abnormal combustion events such as pre-ignition and strong knock are apt to occur (1). The influence of the components of engine oil additives has been pointed out as one possible cause of such abnormal combustion. It has been hypothesized that oil droplets coming from the piston rings or near the cylinder wall disperse throughout the combustion chamber to become sources of

autoignition. It has also been reported that changes in the composition of engine oil additives can affect the tendency for pre-ignition to occur (2)-(3). However, the mechanisms causing these abnormal combustion events are not well understood, and the effect of the individual components of engine oil additives on autoignition is unclear.

For the purpose of ascertaining the effect of engine oil additives on autoignition, combustion experiments were conducted in this study in which selected additives were mixed into test fuels. It is assumed that metal-based additives become more concentrated in the engine oil in the combustion chamber due to dilution of the fuel and evaporation of the base oil. Therefore, combustion experiments were conducted using test fuels into which high concentrations of metal-based additives were mixed in order to examine the relationship between these individual additives and autoignition. It has been

reported that, when a calcium salicylate (CaSa)-based additive, a molybdenum dithiocarbamate (MoDTC)-based additive and a zinc dithiophosphate (ZnDTP)-based additive were mixed into test fuels in the same proportions as they are actually used in engine oil, it was found that the CaSa-based additive had the greatest effect on promoting autoignition. That effect appeared once the additive concentration reached a certain level. In view of those reports, it was decided to investigate the detailed effects of a ZnDTP-based additive and a MoDTC-based additive by conducting combustion experiments in which they were mixed into test fuels at various volume ratios.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Test Fuels

The test engine specifications and experimental conditions used are shown in Table 1. Combustion experiments were conducted using a four-stroke single-cylinder gasoline engine with a side-valve arrangement. Assuming that a mixture of engine oil and gasoline would autoignite, a primary reference fuel having an octane number of 50 (PRF 50) was used as the baseline test fuel into which Zinc (Zn) additive were mixed at zinc concentration of 115 ppm, 570 ppm and 800 ppm. In addition, Molybdenum (Mo) additive were mixed at molybdenum concentration of 140 ppm, 700 ppm and 980 ppm.

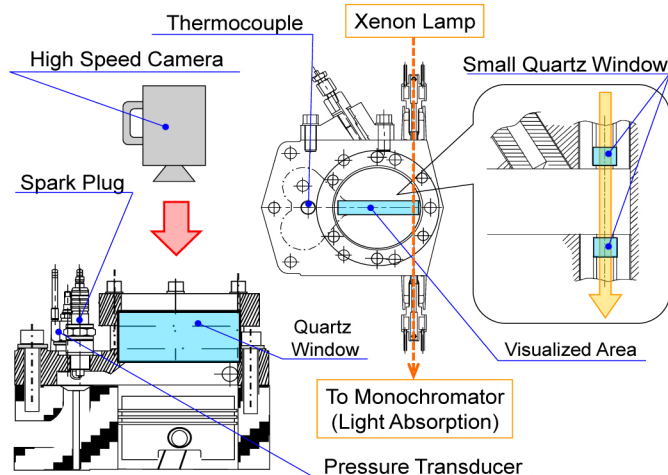


Figure 1. Configuration of test engine

Visualization

The configuration of the measurement equipment used is shown in Fig. 1. A quartz window was provided in the top of the cylinder to enable a rectangular portion of the combustion chamber to be visualized. A high-speed camera was used to obtain photographs of the visualized area for observation of the combustion and knock conditions in the cylinder. Photographs were taken at a frame rate of 40,000 frames/sec. and a resolution of 512 × 128 pixels.

Spectroscopic Measurement

Small quartz windows were also provided in the cylinder head to facilitate absorption spectroscopy (4)-(5). The combustion chamber was irradiated with parallel light from a xenon lamp through a quartz observation window on one side of the cylinder and the transmitted light was sampled through a quartz observation window on the opposite side using an optical fiber cable. The sampled transmitted light was introduced into a monochromator and separated into its spectral components at a wavelength of 293.1 nm, corresponding to the absorption wavelength of formaldehyde (HCHO) that is produced during cool-flame reactions (6). The separated transmitted light was introduced into a photomultiplier tube and converted to an electric signal, which was defined as the transmitted light intensity. The absorbance of HCHO A_{HCHO} was calculated with Eq. (1) below using the transmitted light intensity $E_{\text{HCHO(AVG)}}$ [A.U.] before the occurrence of any reactions as the baseline and the transmitted light intensity E_{HCHO} [A.U.] at any arbitrary crank angle.

$$A_{\text{HCHO}} [-] = \frac{E_{\text{HCHO(AVG)}} - E_{\text{HCHO}}}{E_{\text{HCHO(AVG)}}} \quad (1)$$

EXPERIMENTAL RESULTS AND DISCUSSION

Observation of Visualized Combustion of Test Fuels Containing Additives

Combustion experiments were conducted using test fuels into which Zn and Mo engine oil additives were mixed at various concentration as indicated in Table 1. A transition from a condition of normal combustion to one of abnormal combustion was induced with all of the test fuels by raising the engine temperature. Because the test engine was air-cooled, the spark plug washer temperature T_{SP} was used in this study as the engine temperature.

Table 1. Engine specifications and experimental conditions

Four-stroke Air-cooled Single Cylinder Gasoline Engine	
Bore × Stroke	85 × 70 mm
Displacement	397 cm ³
Valve Arrangement	Side Valves
Engine Speed	1400 rpm
Mixture Ratio	Stoichiometric
Ignition Timing (I.T.)	5 deg. BTDC
Compression Ratio	8.0:1
Test Fuels (Fuel + Additive [ppm])	PRF 50 (Base Condition) PRF 50 + Zn 115,570,800 ppm PRF 50 + Mo 140,700,980 ppm

Figure 2 shows the waveforms that were measured in a series of experiments from normal combustion to knocking operation when using a test fuel containing 115 ppm of the Zn additive. From the top, the vertical axes show the cylinder pressure P [MPa], heat release rate HRR [J/deg.] and HCHO absorbance A_{HCHO} in the end zone of the combustion chamber in relation to the crank angle θ [deg.] along the horizontal axis. The

measured waveforms indicate that the time when autoignition occurred and the rise of the HCHO waveform generally advanced to an earlier crank angle as the engine temperature rose. While this will be shown in scatter graphs later, these results are virtually the same as the waveforms measured for PRF50 alone, which indicates that mixing in 115 ppm of the Zn additive did not have an appreciable effect on combustion.

Figure 3 shows the measured waveforms and visualized combustion images obtained when 570 ppm of the Zn additive was mixed into the fuel. Both the measured waveforms and visualized images indicate that autoignition occurred at an earlier crank angle at higher engine temperatures compared with the results for lower engine temperatures. However, it is also observed that the time when autoignition occurred fluctuated in that temperature range.

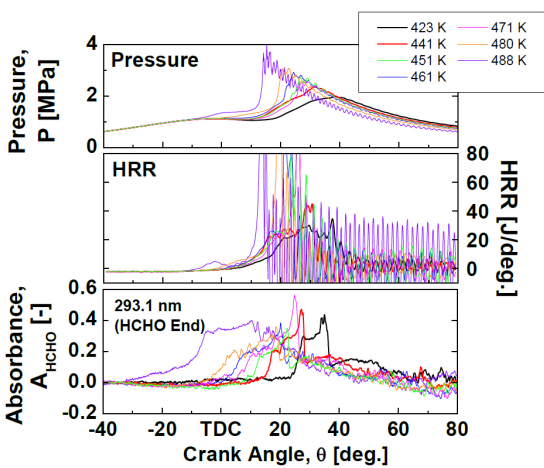


Figure 2. Measured waveforms (Zn 115 ppm)

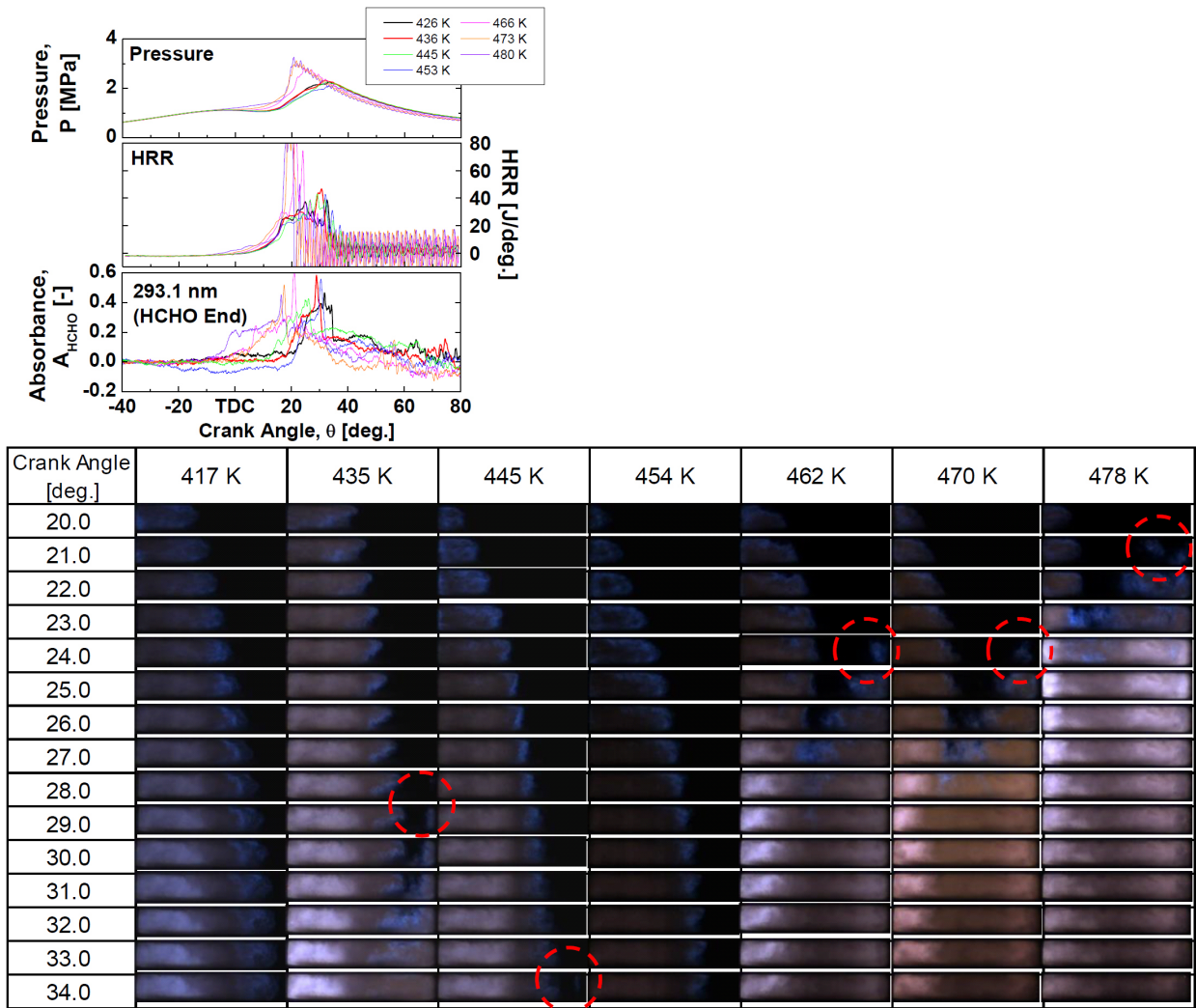


Figure 3. Measured waveforms and flame behavior (Zn 571 ppm)

For example, a comparison of the results for spark plug washer temperature of 445 K and 435 K reveals that autoignition occurred at an earlier crank angle at the latter temperature.

The measured waveforms obtained when 800 ppm of the Zn additive was mixed into the fuel are shown in Fig. 4. Like the

results in Fig. 3, it is observed that the time when autoignition occurred tended to vary as the engine temperature rose from a low to a high level. However, it is seen that the fluctuation became more pronounced than for the fuel with 570 ppm of the additive.