

Abnormal Combustion Induced by Combustion Chamber Deposits Derived from Engine Oil Additives in a Spark-Ignited Engine

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ABSTRACT

Although metallic compounds are widely known to affect combustion in internal combustion engines, the potential of metallic additives in engine oils to initiate abnormal combustion has been unclear. In this study, we investigated the influence of combustion chamber deposits derived from engine oil additives on combustion in a spark-ignited engine. We used a single-cylinder four-stroke engine, and measured several combustion characteristics (e.g., cylinder pressure, in-cylinder ultraviolet absorbance in the end-gas region, and visualized flame propagation) to evaluate combustion anomalies. To clarify the effects of individual additive components, we formed combustion products of individual additives in a combustion chamber prior to measuring combustion characteristics. We tested three types of metallic additives: a calcium-based detergent, a zinc-based antiwear agent, and a molybdenum-based friction modifier. Measurements of combustion characteristics after deposit formation revealed that the deposits derived from the calcium and zinc compounds facilitated auto-ignition and increased knock intensity. However, the deposits from molybdenum compounds showed no significant impact on auto-ignition. Our results showed that the chemical composition of combustion chamber deposits has specific effects relating to abnormal combustion in spark-ignited engines.

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INTRODUCTION

Prevention of auto-ignition, and its resulting abnormal combustion, is a longstanding problem for spark-ignited internal combustion engines. This type of abnormal combustion triggers engine knock, which causes not only uncomfortable noises but also engine damage. Although high-compression ratios, lean air/fuel mixtures, and/or high-boost pressures result in more frequent auto-ignition, modern engines inevitably tend to implement such engine configurations to improve fuel efficiency because of strict emissions regulations. Recent direct-injected highly boosted "down-sized" engines, which were developed to meet the latest emissions regulations, have been reported to elicit low-speed pre-ignition (LSPI), which spontaneously ignites the air/fuel mixture before the spark plug fires, and causes severe engine knock. It is necessary to reveal the detailed mechanism of auto-ignition and develop technology to prevent the phenomenon.

Engine oils may significantly contribute to auto-ignition [1, 2]. Engine oil leakage into combustion chambers through valve stem seals or piston rings potentially perturbs the chemical reaction in combustion chambers. When engine oils

contaminate an air/fuel mixture, auto-ignition could be initiated because the spontaneous ignition temperature of engine oils is generally much lower than other fuels, due to the different carbon number of their hydrocarbon contents. Hydrocarbons are likely root causes of engine oil-induced auto-ignition. However, the latest study of LSPI showed that engine oil additive chemistry strongly affects the frequency of LSPI [3]. This indicates that nonhydrocarbon metallic components of engine oils, such as detergents, can be responsible for engine oil-induced auto-ignition. Although metallic compounds are known to affect combustion in the field of fuel additive technology, the link between engine oil additives and combustion has been poorly understood. To better understand combustion and improve engine technology, we need to elucidate the mechanisms in engine oil additives that contribute to auto-ignition.

In this study, we investigated the effects of the deposits of engine oil additives on combustion in a spark-ignited engine. When engine oils enter a combustion chamber, nonvolatile engine oil additives, such as metallic compounds, would be expected to deteriorate and accumulate in the combustion

chamber. Such deposits might have substantial effects on combustion. We used a single-cylinder four-stroke engine and, to form additive-derived deposits in its combustion chamber, engine oil additives were diluted into fuels that were introduced to the engine in operation. Three typical metallic additives were tested: a calcium-based detergent, a zinc-based anti-wear agent, and a molybdenum-based friction modifier. We found that calcium-derived and zinc-derived deposits strongly advance auto-ignition timing, whereas molybdenum-derived deposits do not.

METHODS

Engine

We used the air-cooled single-cylinder four-stroke engine that was developed in house for research purposes and used for research published previously [4]. The engine is schematically shown in figure 1, and the detailed specification is provided in table 1. We implemented the so-called 'L-head' side-valve system to directly observe the auto-ignition flame. The head cover of this engine was made partly of transparent quartz to visualize the inside of the combustion chamber. A high-speed camera (FASTCAM SA1.1, Photron) recorded the inside of the combustion chamber. In this engine, the spark ignition flame propagates from the valve-side end, and the auto-ignition flame appears at the opposite end. At the auto-ignition end, ultraviolet light absorbance at the wavelength of 293.1 nm was measured using an optical system based on a Xenon lamp, and a monochromator was used to monitor the quantity of aldehydes, which transiently emerge in the combustion reaction and rapidly disappear once ignited. We determined auto-ignition timing based on the drop in this ultraviolet absorbance signal. The combustion chamber was equipped with pressure transducer, which recorded the temporal variation of in-cylinder pressure during the experiments. We defined the maximum amplitude of the pressure signal oscillation as knock intensity. For a representative temperature of the engine in operation, we measured spark plug washer temperature with a thermocouple probe.

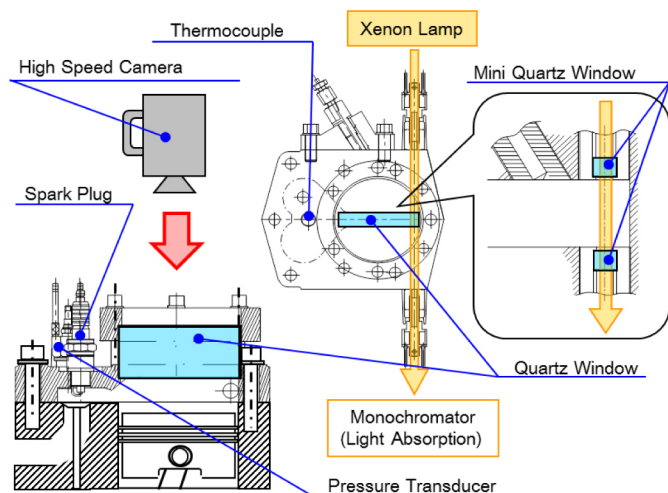


Figure 1. Schematic representation of the engine used in this study.

Table 1. Specification and test configuration of the engine.

Displacement	397 cc
Stroke	85 mm
Bore	70 mm
Compression ratio	8:1
Engine speed	1400 rpm
Load condition	Full load / WOT (wide open throttle)
Air/fuel ratio	Stoichiometric
Ignition timing	-5° ATDC (after top dead center)
Intake air temperature	304 ± 1 K
Boost pressure	98 kPa (natural aspiration)
Charging efficiency	70-80%

Fuels

Base Fuel

Instead of gasoline, we used primary reference fuel 50 (PRF50), which is an equal-volume mixture of isooctane and n-heptane, as a base fuel. When we used gasoline, auto-ignition occurred so rarely that we were unable to compare the characteristics of auto-ignition with baseline and other conditions. PRF50 allowed a detailed analysis of deposit-induced changes in combustion characteristics.

Engine Oil Additives

We used three organometallic additives typically included in engine oils: calcium salicylate (CaSa), zinc dithiophosphate (ZnDTP), and molybdenum dithiocarbamate (MoDTC). CaSa is frequently used as a detergent additive to improve engine cleanliness. This additive does not contain sulfur, phosphorus, or any metallic atom other than calcium. ZnDTP is primarily used as an antiwear agent, and acts as an antioxidant as well. Most passenger-car engine oils contain ZnDTP to achieve sufficient engine protection performance. ZnDTP contains zinc, sulfur, and phosphorus. The atomic ratio of these elements in the ZnDTP used in this study was Zn:S:P = 1:4:2. MoDTC is a friction modifier that forms a low-friction boundary film on metal surfaces, and reduces mechanical loss in engines. Some top-tier fuel economy engine oils are formulated with MoDTC. The MoDTC used in this study contains molybdenum and sulfur at the atomic ratio of Mo:S = 2:7.

Fuel Preparation

CaSa and ZnDTP were diluted into a base fuel with the dosage of 2.0 vol% ([Ca] = 2200 ppm and [Zn] = 2700 ppm). MoDTC was diluted into a base fuel with the dosage of 0.7 vol% ([Mo] = 1000 ppm), because MoDTC is less dispersive than CaSa and ZnDTP, and it easily precipitates at high dosage. The additive-containing fuels were well stirred and dispersed before the experiment.