

Pre-Ignition of Gasoline-Air Mixture Triggered by a Lubricant Oil Droplet

Mitsuaki Ohtomo, Hiroshi Miyagawa, and Makoto Koike
Toyota Central R&D Labs Inc.

Nozomi Yokoo and Koichi Nakata
Toyota Motor Corp.

ABSTRACT

This paper presents the effects of a lubricant oil droplet on the start of combustion of a fuel-air mixture. Lubricant oil is thought to be a major source of low-speed pre-ignition in highly boosted spark ignition engines. However, the phenomenon has not yet been fully understood because its unpredictability and the complexity of the mixture in the engine cylinder make analysis difficult.

In this study, a single oil droplet in a combustion cylinder was considered as a means of simplifying the phenomenon. The conditions under which a single oil droplet ignites earlier than the fuel-air mixture were investigated. Tests were conducted by using a rapid compression expansion machine. A single oil droplet was introduced into the cylinder through an injector developed for this study. The ignition and the flame propagation were observed through an optical window, using a high-speed video camera.

The test results showed that the ignition timing triggered by the oil droplet became earlier as the droplet diameter decreased and the temperature increased. Except under some conditions, however, ignition delay was later than that of a gasoline mixture. The early triggering of combustion followed by flame propagation required the introduction of a heated oil droplet. The probability of flame propagation initiated by the oil droplet decreased with the temperature of the droplet. Numerical simulations indicated the same tendency. The test results also showed that the probability of ignition changed with the dilution ratio and the ignitability of the mixture. It was notable that the dilution with N_2 and CO_2 decreased more than the fuel RON.

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INTRODUCTION

Current highly boosted spark ignition engines achieve a similar or even higher level of break mean effective pressure than diesel engines. Unlike in the case of diesel engines, the performance of spark ignition engines is limited by the occurrence of knock or pre-ignition. At low speeds, in particular, abnormal combustion called as low-speed pre-ignition (LSPI) is a major issue affecting an increase in the torque. LSPI is a stochastic phenomenon whereby the fuel-air mixture is ignited earlier than the spark timing, leading to flame propagation that results in a heavy knock.

There have been several studies into the effects of the mixture conditions as well as the characteristics of the lubricant oil on the frequency of occurrence of LSPI in boosted spark ignition engines [1, 2, 3, 4, 5]. It has been clarified that the frequency of LSPI increases with an increase in boost pressure, while it decreases with an increase in the EGR ratio. The lubricant oil

additives such as the Ca-based detergent, MoDTC and ZnDTP also influenced the frequency of occurrence of LSPI. An optical investigation found that the pre-ignition origins were spread over a wide range [6]. This indicates that there is a possibility of contaminants in the combustion cylinder initiating the combustion of the fuel-air mixture. However, it is not easy to investigate the conditions under which LSPI occurs. One reason for this is that the phenomenon is a stochastic event. The difficulty in identifying the local ignition conditions due to the temperature and fuel distributions also makes analysis difficult. It has been reported that auto-ignition was observed before and after TDC without fuel injection in 2-stroke gas engines [7]. This indicates the possibility of auto-ignition being caused by the lubricant oil. Some numerical simulations proposed that a droplet whose physical and chemical properties are represented as n-heptane and n-hexadecane could act as an ignition source for the fuel-air mixture [6, 8]. These results indicate that an oil droplet constitutes a major

source of LSPI. However, ignition initiated by an oil droplet followed by flame propagation has not been proved. The effects of a droplet and the mixture conditions on ignition have not been clarified.

In this study, the effects of a contaminant on the initiation of combustion were investigated. A single lubricant oil droplet in a combustion cylinder was considered as a contaminant to simplify the phenomenon. The objective of this study was to clarify the conditions under which a single oil droplet initiates the combustion of a fuel-air mixture.

METHODOLOGY

Experiment

Control of Droplet Diameter and Temperature

In this study, ignition of a single oil droplet for which the diameter and temperature could be controlled was investigated by using a rapid compression expansion machine (RCEM). An injector was developed whereby the diameter of the droplet can be controlled, as shown in Figure 1. The needle was driven in minimal displacement by using the piezo actuator so that a single droplet could be injected from the nozzle. The droplet diameter could be varied between 60 and 500 μm by varying the nozzle diameter and drive pulse. For example, Figure 2 shows the droplet diameters over 25 tests with a nozzle diameter of 20 μm . The diameters were measured from each droplet image. There was little difference of the diameter. The droplet diameter was obtained by taking an average over 15 tests.

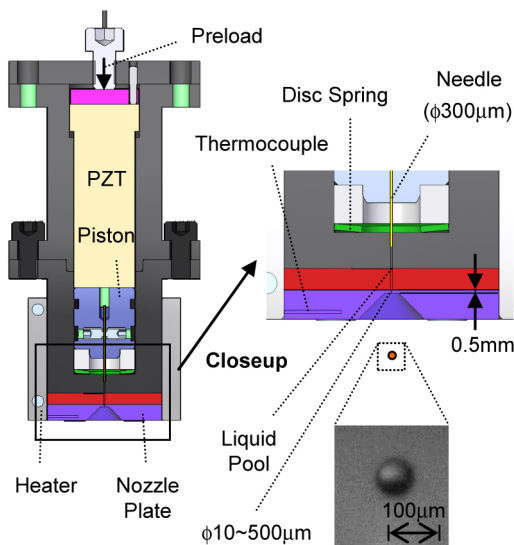


Figure 1. Single droplet injector

The temperature of the droplets could also be controlled. The droplet was heated through a heating pipe with an inner diameter of 6 mm, installed between the injector and the cylinder. The droplet temperature was measured at a point 55 mm below the exit of the pipe. This position corresponded to that of a droplet at the start of the compression in an ignition test. The temperature measurement method of the droplet is

described as follows. The droplet temperature (T_d) was compared with the thermocouple temperature (T_{tc}) when the droplet came into contact with the heated thermocouple. An uncoated 70- μm thermocouple was used to increase the sensitivity. For example, Figure 3 shows T_{tc} and the time derivative of T_{tc} (dT_{tc}/dt) after heating of the thermocouple shut off. In (a), dT_{tc}/dt increased when the droplet contacted with the thermocouple. This showed that T_d was higher than T_{tc} . On the other hand, T_d was lower than T_{tc} in the case of (b) because dT_{tc}/dt decreased. It was also observed that there was little change in dT_{tc}/dt after the injection of the droplet. This indicated that the difference between T_{tc} and T_d was small. Figure 4 shows the probability of dT_{tc}/dt changing to a positive or negative value at every 5°C. The test was conducted five or more times for each range. The value of dT_{tc}/dt changed positive and negative between 280 and 300°C. In this case, the droplet temperature was defined as 290°C (Center value). The droplet temperature was set between 80 and 335°C by varying the heating pipe temperature.

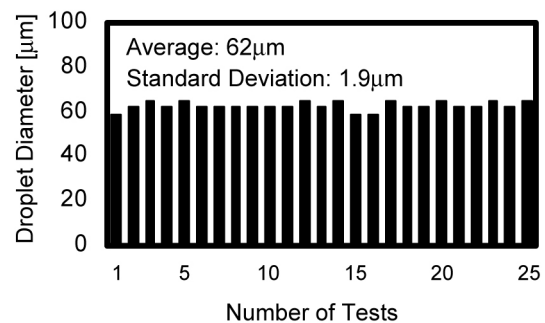


Figure 2. Variations in droplet diameter

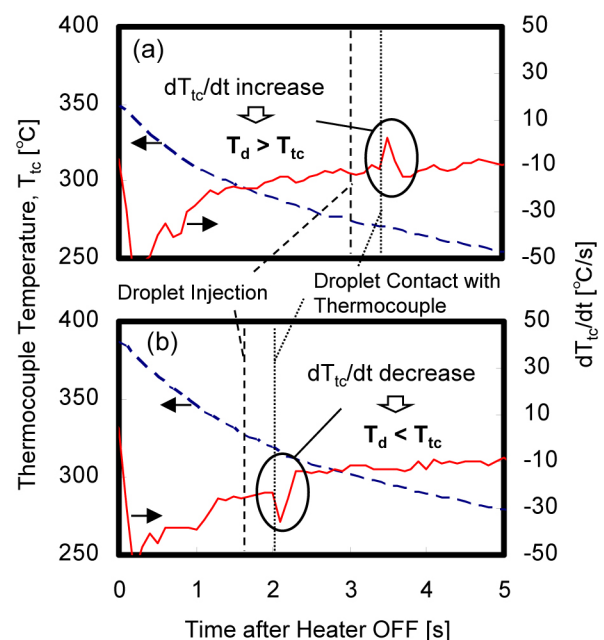


Figure 3. Histories of T_{tc} before and after droplet contact with thermocouple ((a) $T_d > T_{tc}$, (b) $T_d < T_{tc}$)

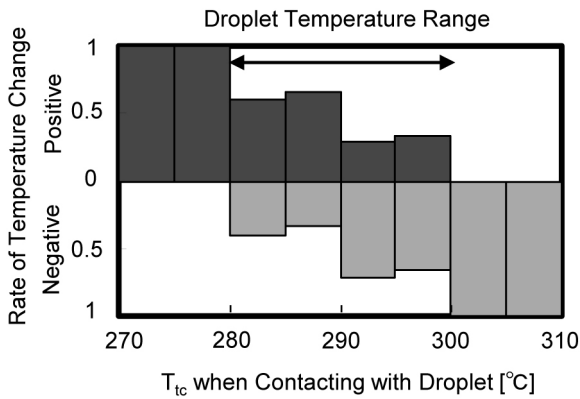


Figure 4. Droplet temperature estimation

Experimental Setup

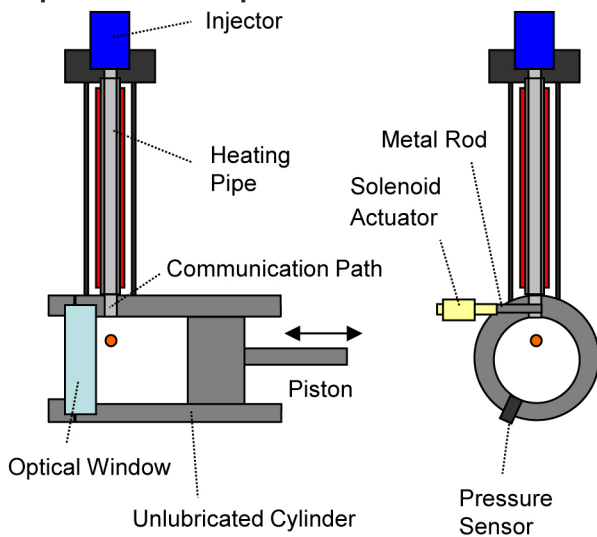


Figure 5. Experimental setup

Figure 5 shows the setup used for the experiments. The combustion cylinder was filled with air or a fuel-air mixture. A droplet was introduced into the cylinder through a communication path. Subsequently, the path was closed by a metal rod and the gas in the cylinder was compressed with the piston. No lubricating oil was applied to between the piston and the cylinder. Therefore, there were no contaminants except for the droplet in the cylinder. When the droplet reached the cylinder wall before ignition, it was suspended in the center of the cylinder with 50- μ m tungsten wires. The pressure history in the cylinder was measured by a pressure sensor (Kistler, Type 6125B01). The combustion in the cylinder was observed through an optical window, using a shadowgraph technique with a high-speed video camera (Nac Image Technology, MEMRECAM HX-3). Figure 6 shows the optical system. When the ignition could not be clearly observed, the ultraviolet light emitted by the occurrence of the ignition was measured using an image intensifier and a cut-off filter of more than 330 nm. The compression duration was 25 ms. This corresponded to an engine speed of 1200 rpm. When the cylinder was filled with air, the piston held at TDC after compression. In the case of a fuel-air mixture, the auto-ignition of the mixture occurred and

the pressure in the cylinder increased rapidly if the piston held at over 5ms. The rapid pressure increase has a possibility of damaging the optical system. Therefore, the piston was moved to BDC after being held at TDC for 5 ms. Commercially available lubricant base oil was used (SK Lubricants, YUBASE 6, GrIII). Table 1 shows the characteristics.

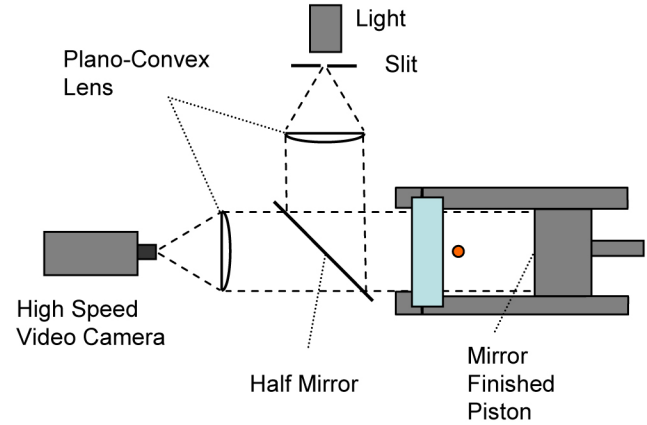


Figure 6. Optical setup of shadowgraph system

Table 1. Characteristics of tested oil

Density	0.843 g/ml
Kinematic Viscosity @ 40°C	36.7 cSt
Kinematic Viscosity @ 100°C	64.5 cSt
Viscosity Index	128
Noack Volatility	7.3%

Numerical Analysis

The ignition delay for the fuel-air mixture with a single droplet was calculated in order to investigate the effects of the droplet conditions on ignition. For this analysis, the following was assumed.

- The droplet, which is spherically symmetrical, remains stationary within the mixture.
- The temperature distribution in the liquid phase is uniform.

For the liquid phase, the following equations were used.

$$\frac{dT_d}{dt} = \frac{\frac{dQ}{dt} + L_v \frac{dm}{dt}}{V \rho_d C_{pd}} \quad \text{Eq.(1)}$$

$$\frac{dm}{dt} = -\pi d \rho_d S h \ln(1+B) \quad \text{Eq.(2)}$$

Where Q , L_v , m , V , ρ_d , C_{pd} , d , D , Sh and B are heat from gas to droplet, latent heat of vaporization, mass of droplet, volume of droplet, density of liquid, specific heat of liquid, droplet diameter, diffusion coefficient, Sherwood number, and transfer number, respectively.