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Research Report

Ignition of Fuel-air Mixture by a Lubricant Oil Droplet

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ABSTRACT Highly-boosted spark ignition engines are known to exhibit an abnormal combustion phenomenon known as low-speed pre-ignition (LSPI), and the ignition of lubricant oil droplets is thought to be one possible mechanism for LSPI. However, the oil droplet ignition conditions are not yet well understood. In this study, the conditions under which a single oil droplet initiates the combustion of a fuel-air mixture under high temperature and pressure were experimentally investigated using a rapid compression and expansion machine. The ignition delay of the oil droplet was found to decrease as the initial droplet diameter decreased and as the initial droplet temperature increased, because the ignition process is controlled by evaporation. At an initial droplet temperature above 250°C, the vaporized oil ignited before the gasoline-air mixture, in which case the combustion of the gasoline-air mixture around the droplet was initiated. The results of numerical simulations show that the oil droplet temperature increases above 250°C when the droplet is heated by combustion gases remaining in the chamber from the previous cycle. These results indicate that heated droplets remaining in the combustion chamber until the next cycle can possibly initiate LSPI.

KEYWORDS SI Engine, Boosted Engine, Pre-ignition, Lubricant Oil, Ignition Delay

1. Introduction

Recently, highly boosted spark ignition (SI) engines that exhibit improved fuel consumption and torque have been developed. Unfortunately, these engines can undergo an abnormal combustion process termed low-speed pre-ignition (LSPI), which is a major issue at low speeds and under highly boosted conditions. LSPI is a phenomenon in which the fuel-air mixture ignites before the spark timing, leading to flame propagation that results in a heavy knock.

Many studies of LSPI have been conducted. As an example, optical investigations have been performed in boosted SI engines, and it has been reported that airborne contaminants such as deposits and oil droplets in the combustion chamber can serve as early ignition sources to initiate the combustion of the fuel-air mixture.(1-3) However, it is not easy to clarify the LSPI mechanism, partly because LSPI is a stochastic phenomenon. The main difficulty lies in identifying the local ignition conditions, because the ignition point is different each time. Other studies have investigated the effects of the engine operating conditions on LSPI.(4-8) These have shown that the frequency of LSPI is changed not only by variations in the fuel-air mixture but also by the characteristics of the lubricant oil. The occurrence of LSPI in heavy duty gas engines has also been reported.(9) In that study, the ignition of the lubricant oil in the combustion chamber was observed even without fuel injection. The main component of lubricant oil is normal paraffin, while iso-paraffin and aromatic hydrocarbons are present in gasoline. Therefore, the oxidation reactivity of lubricant oil is actually higher than that of gasoline. These prior findings indicate that the auto-ignition of lubricant oil droplets can trigger the early combustion of the fuel-air mixture. However, there have been few studies concerning the auto-ignition of lubricant oil droplets. In order to investigate the effects of oil droplets on LSPI, the ignition conditions of these droplets must be clarified.

The objective of the present study was to examine the conditions under which a single oil droplet can initiate the combustion of a fuel-air mixture. First, the auto-ignition of an oil droplet and the combustion of a fuel-air mixture under high temperature and high pressure conditions were assessed, using a rapid compression and expansion machine (RCEM).

Subsequently, the conditions that the oil droplet experiences in an engine combustion chamber were estimated by numerical simulations. Based on these results, the conditions under which oil droplets lead to LSPI are discussed.

2. Experimental

2. 1 Experimental Setup

In this study, a single lubricant oil droplet was sent into the combustion chamber of an RCEM, and the initial droplet diameter and temperature were varied. **Figure 1** shows the injector used in these trials to introduce single droplets into the combustion chamber. Each droplet was injected from the nozzle by the fast displacement of a needle using a piezo actuator. The droplet diameter was controlled by varying the nozzle diameter and the duration of the signal pulse. **Figure 2** presents the experimental setup, and Fig. 2(a) shows the injector. The injector and a heating pipe were located above the combustion chamber, and the droplet temperature was varied by heating the droplet as it passed through the heating pipe after injection. The droplet diameter and temperature were varied over the ranges of 60-500 μm and 80-335°C, respectively. Initially, either pure air or a fuel-air mixture were transferred into the combustion chamber. The droplet was then injected and the chamber was sealed by moving a metal rod to block the heated injection pathway through which the droplet had entered. Subsequently, the gas in the cylinder was compressed with the piston. In this apparatus, the piston moved without lubrication to exclude the effects of lubricant oil other than the introduced droplet. When the ignition delay was long, the droplet was found to reach the cylinder wall before ignition. To avoid this, the droplet was suspended in the center of the combustion chamber using a pair of crossed 50 μm tungsten wires, as shown in Fig. 2(b).

The pressure in the cylinder over time was measured using a pressure sensor, and the combustion process was observed through an optical window using a shadowgraph technique in conjunction with a high speed video camera. The gas pressure and temperature at the end of the compression were set at 1.9 MPa and 530°C, which are the typical conditions under which LSPI occurs in an engine. The compression time from bottom dead center (BDC) to top dead center (TDC) was varied between 25 and 375 ms, corresponding to engine speeds between 1200 and 80 rpm. A commercially-available lubricant base oil that does not contain additives was used (SK Lubricants, YUBASE 6, GrIII, **Table 1**).

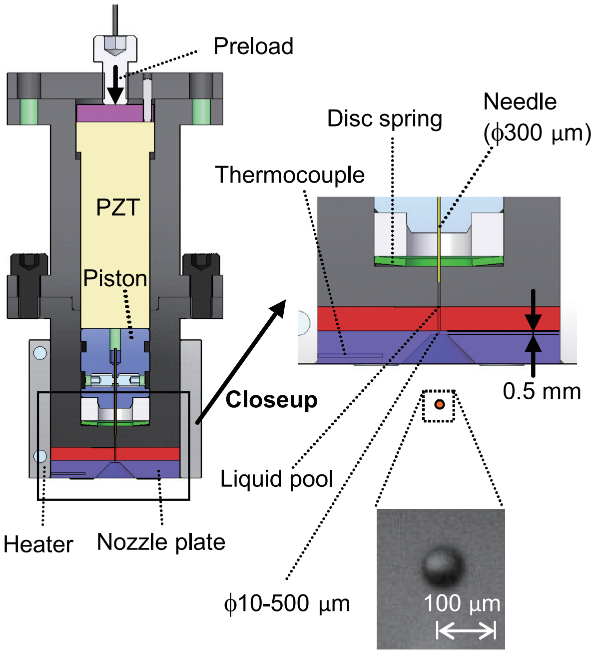

Fig. 1 Single droplet injector.

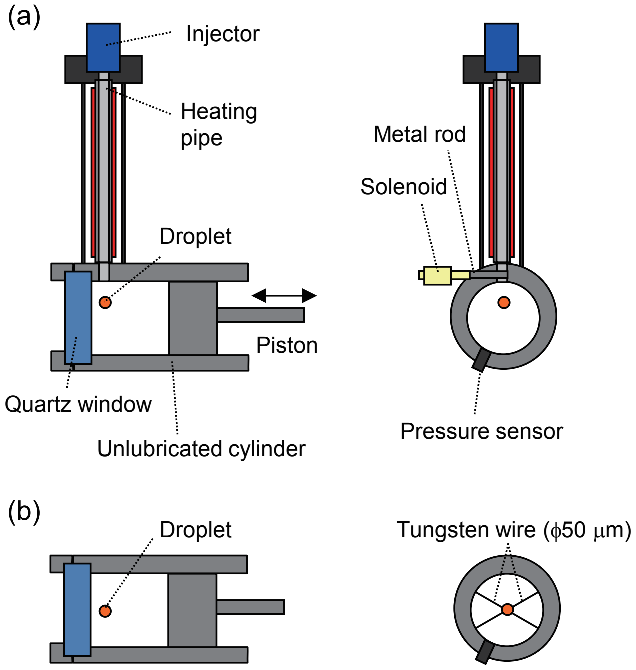

Fig. 2 Experimental setup.

2. 2 Experimental Results

2. 2. 1 Ignition in Air

The ignition delay of a single oil droplet in air was initially measured. First, the effects of the initial droplet diameter (d_0) on the ignition delay were investigated, varying d_0 from 60 to 500 μm at an initial droplet temperature (T_{d0}) of 80°C. In this test, the piston was held at TDC after compression and the compression duration (t_{comp}) was 25 ms. When d_0 was over 100 μm, the droplet was suspended in the center of the chamber, as shown in Fig. 2(b). **Figure 3** summarizes the effects of d_0 on the ignition delay, and it is evident that the ignition delay becomes smaller with decreases in d_0. The auto-ignition delay of a stoichiometric gasoline-air mixture (τ_g) was measured under the same compression conditions for comparison purposes, and the resulting data are also shown in Fig. 3. The ignition delay of the droplet in this test was found to be longer than τ_g. If the ignition of the droplet does indeed trigger the combustion of the fuel-air mixture, the droplet must ignite earlier than the fuel-air mixture. This result suggests that there is little possibility that an oil droplet at T_{d0} = 80°C will initiate the combustion of the fuel-air mixture.

The effects of T_{d0} on the ignition delay were also investigated, during which trials d_0 was above 400 μm and the ignition delay of the droplet was 200 ms, as shown in Fig. 3, at T_{d0} = 80°C. **Figure 4** presents images of the combustion chamber at T_{d0} and d_0 values of 335°C and 410 μm, respectively. The oil droplet is seen to fall through the chamber and at −19.0 ms and −9.0 ms vaporization is observed within the trajectory of the droplet because of the high droplet temperature. At 2.0 ms, a change in the gas density is observed along the trajectory at the top of the chamber, and at 21.0 ms the droplet ignites, emitting a luminous flame. Ultraviolet light emission was observed at the end of the compression using an image intensifier in conjunction with a 330 nm shortpass filter. This result suggests that the change in the gas density observed at 2.0 ms resulted from oil vapor ignition at a distance from the droplet. In this paper, ignition in the immediate surrounding of the droplet is defined as droplet ignition, while oil vapor ignition away from the droplet is defined as vapor ignition. These experiments were conducted repeatedly under the same conditions, and vapor ignition and droplet ignition were observed in 9 out of 10 trials. **Figure 5** shows the effects of T_{d0} on the variations of the vapor and droplet ignition delays with τ_g. The droplet ignition delay decreases

Table 1 Characteristics of tested oil.

Density	0.843 g/ml
Kinematic viscosity @ 40 ℃	36.7 cSt
Kinematic viscosity @ 100 ℃	64.5 cSt
Viscosity index	128
Noack volatility	7.3%

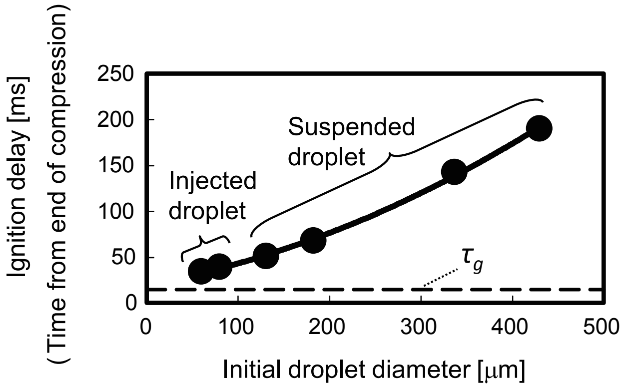

Fig. 3 Ignition delay with initial droplet diameter, cylinder gas: air, T_{d0} = 80˚C.

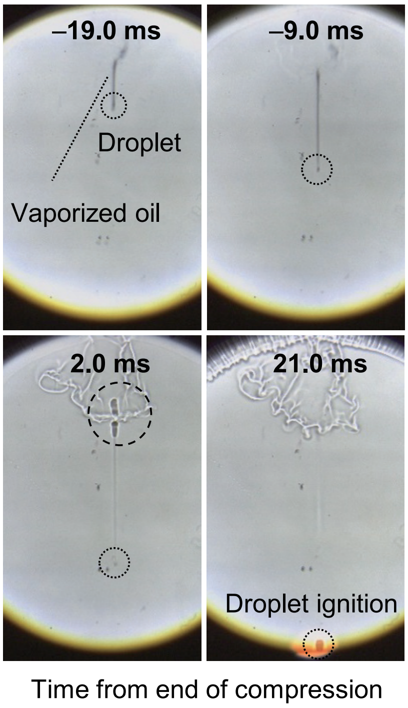

Fig. 4 Observed droplet behavior and ignition, cylinder gas: air, d_0 = 410 μm, T_{d0} = 335˚C.

with increases in T_{d0}. In the case of T_{d0} = 335°C, the droplet ignition delay was almost the same as τ_g. Above 290°C, vapor ignition was observed and the associated ignition delay was less than τ_g. In the case of T_{d0} = 290°C, vapor ignition occurred in 2 out of 10 trials. This result demonstrates that an oil droplet heated to a high temperature before compression can possibly trigger the combustion of the fuel-air mixture, even if d_0 is over 400 μm.

As seen in Figs. 3 and 5, the droplet ignition delay value becomes smaller as d_0 decreases and as T_{d0} increases. These results suggest that evaporation is a determining factor in the ignition process. In these same two figures, the gas temperature around the droplet increases quickly because the compression rate is high. Under these conditions, the droplet temperature does not coincide with the gas temperature. At slower compression rates, the droplet temperature at the end of the compression will be high because the duration over which the droplet is heated by the gas is increased. This leads to increasing amounts of the oil vapor and, as a result, the ignition delay of the droplet is reduced. Therefore, there is the possibility that an oil droplet with a low T_{d0} can ignite the fuel-air mixture when t_{comp} is slow. The effects of t_{comp} on the ignition of the oil droplet were therefore assessed. In these trials, the piston was expanded just after the end of the compression, without stopping at TDC, and t_{comp} was varied between 25 and 375 ms while T_{d0} was set to 80°C, and d_0 was 80, 150, or 200 μm. The expansion duration was also the same as the compression duration. **Figure 6** summarizes the effects of t_{comp} on the ignition delay at T_{d0} = 80°C. A droplet with d_0 = 80 μm was found to ignite when t_{comp} was over 200 ms, while ignition was not observed in the case of t_{comp} < 200 ms. Ignition occurred before the end of the compression at t_{comp} = 300 ms and when d_0 was 150 or 200 μm, the droplet did not ignite in the case of t_{comp} < 375 ms. The minimum t_{comp} required for droplet ignition was increased with increases in the value of d_0. In contrast to the results shown in Fig. 4, vapor ignition was not observed under the test conditions. In the measurement τ_g, the stoichiometric gasoline-air mixture was compressed and expanded. The results are also shown in Fig. 6. The gasoline-air mixture ignited when t_{comp} was over 100 ms, and ignition occurred earlier as t_{comp} became larger. In the case of t_{comp} = 200 ms, the ignition delay of a droplet with d_0 = 80 μm was longer than τ_g, and there was little difference between the ignition of the droplet and τ_g when t_{comp} was 300 ms. This result suggests that the oil droplet does not initiate the combustion of the gasoline-air mixture at shorter t_{comp} values because the ignition of the gasoline-air mixture occurs earlier than that of the droplet.

2. 2. 2 Ignition in Fuel-air Mixture

Next, a single oil droplet was introduced into a stoichiometric gasoline-air mixture in order to investigate the probability that the ignition of the oil droplet triggers the combustion of the mixture. In this test, the piston was moved to BDC after being held at TDC for 5 ms because the rapid pressure increase resulting from auto-ignition of the fuel-air mixture

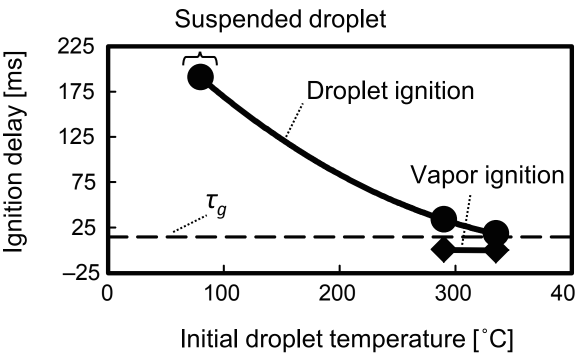

Fig. 5 Ignition delay with initial droplet temperature, cylinder gas: air, d_0 = 400-500 μm.

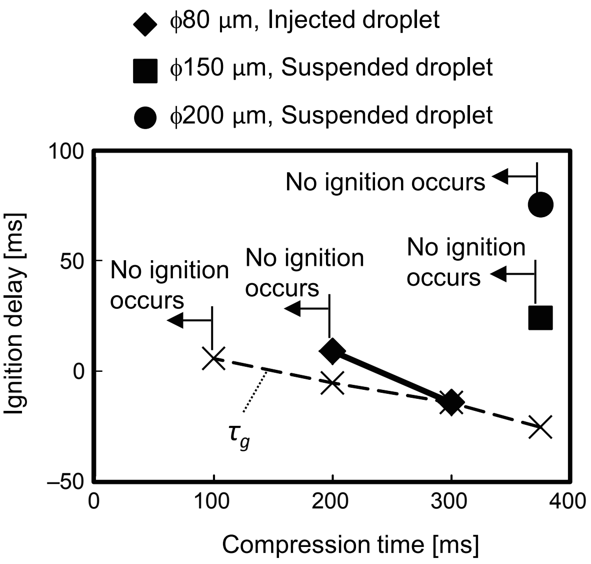

Fig. 6 Ignition delay with compression time, cylinder gas: air, T_{d0} = 80˚C.

might otherwise have damaged the optical system.

The trials were conducted by varying d_0 between 60 and 500 μm with T_{d0} = 120°C and t_{comp} = 25 ms. Neither vapor nor droplet ignition was observed regardless of the value of d_0, nor did the gasoline-air mixture combust, in good agreement with the results expected from Fig. 3.

The effects of T_{d0} were also investigated, and **Fig. 7** shows images of a droplet in the chamber with T_{d0} = 335°C, d_0 = 410 μm and t_{comp} = 25 ms. The oil droplet falls in conjunction with evaporation, as also observed in Fig. 4. At 0.6 ms, vapor ignition occurs at the top of the cylinder, after which flame propagation is observed from the ignition point. Around 5 ms, droplet ignition is seen. Using the same conditions, this experiment was conducted repeatedly, and flame propagation was found to occur in 23 out of 30 trials. When vapor ignition took place, it always resulted in flame propagation. In addition, droplet ignition sometimes occurred in conjunction with ignition of the gasoline-air mixture. **Figure 8** shows the effects of droplet temperature on the probability of flame propagation, from which it is evident that the probability decreased with T_{d0}. Below T_{d0} = 250°C, no flame propagation of the fuel-air mixture was observed.

Next, the combustion of the gasoline-air mixture initiated by the oil droplet was investigated while varying t_{comp}. In this test, T_{d0} = 120°C and d_0 = 150 μm. In the case of t_{comp} = 50 ms, neither ignition of the oil droplet nor the combustion of the gasoline-air mixture occurred while, when t_{comp} was over 100 ms, the gasoline-air mixture ignited earlier than the oil droplet. The oil droplet therefore did not affect the combustion of the gasoline-air mixture. This is because the ignition delay of the gasoline-air mixture was shorter than that of the oil droplet, meaning that the combustion of the fuel-air mixture was initiated by the oil droplet only if the ignitability of the fuel was low. The test was subsequently performed after changing from gasoline to methane, which has lower ignitability than gasoline. A stoichiometric methane-air mixture without an oil droplet did not ignite regardless of t_{comp}. **Figure 9** shows images of the combustion chamber in the case of t_{comp} = 375 ms, in which the oil droplet ignites at −7.1 ms and flame propagation is observed from the ignition point. The droplet ignition initiated the

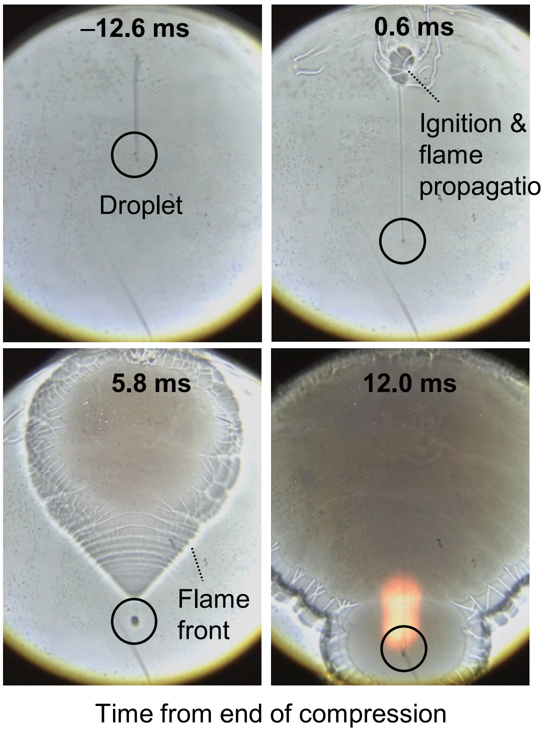

Fig. 7 Ignition and flame propagation in gasoline-air mixture, T_{d0} = 335°C, d_0 = 410 μm, t_{comp} = 25 ms.

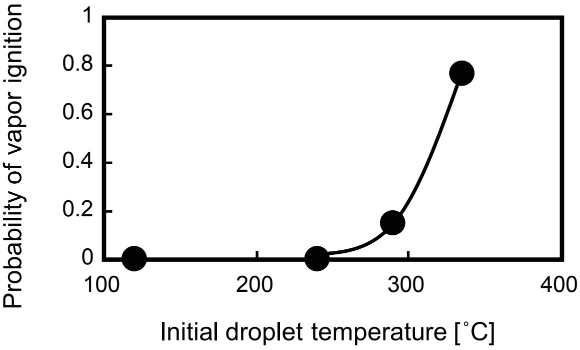

Fig. 8 Effect of droplet temperature on vapor ignition, d_0 = 400-500 μm, t_{comp} = 25 ms.

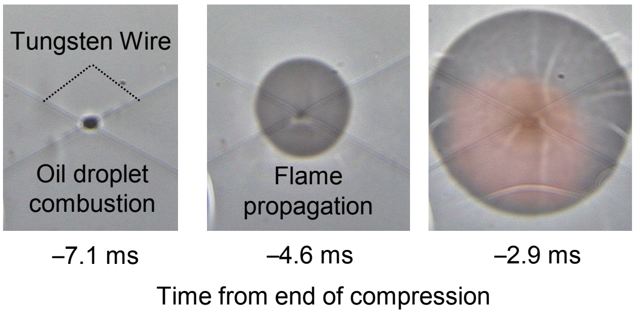

Fig. 9 Observed droplet ignition and flame propagation in CH_4-air mixture, T_{d0} = 120˚C, d_0 = 150 μm, t_{comp} = 375 ms.

combustion of the methane-air mixture. Under these conditions, combustion triggered by the ignition of the droplet inevitably occurred. In contrast, no ignition was observed when t_{comp} was less than 300 ms.

Figure 10 summarizes the conditions under which the fuel-air mixture was ignited by the auto-ignition of the oil vapor or droplet. The horizontal axis shows the engine speed, corresponding to the compression time, and the circle symbols indicate that the combustion of the fuel-air mixture was initiated by the oil droplet, while the crosses show that combustion did not occur. When the ignition of the oil droplet occurred earlier than the ignition of the fuel-air mixture, the combustion of the fuel-air mixture is assumed to have been initiated by the droplet. In the case of high compression speed, oil vapor ignition occurred when the initial droplet temperature was high, so the ignition delay was shorter than that of the gasoline-air mixture. Therefore, the flame propagation of the fuel-air mixture was initiated by the oil droplet. In the case of low compression speed, droplets with low initial temperature also ignited. Under these conditions, the ignition delay of the droplet was longer than that of the gasoline-air mixture, so the gasoline-air mixture ignited without the droplet. In contrast, the ignition delay of the droplet was shorter than that of the methane-air mixture, which had lower reactivity, meaning that the combustion of the fuel-air mixture was initiated by the ignition of the droplet.

These results were assessed based on phenomena observed in actual engines. Some papers have reported that oil droplets are released from the piston crevice area. The temperature of the lubricant oil in this region is equal to or lower than the cylinder temperature, which will always be below 200°C. This temperature is too low to initiate the combustion of the fuel-air mixture at high engine speed, suggesting that the oil droplets just after release from the piston crevice area do not initiate the combustion of the fuel-air mixture in automotive gasoline engines. Conversely, at lower engine speeds, these droplets could potentially initiate flame propagation of the fuel-air mixture. This means that LSPI may be triggered by the ignition of the oil droplets just after release from the crevice area in heavy duty and low speed gas engines.(9)

The possibility that high temperature oil droplets could be present in the engine cylinder was also considered. The oil droplets released from the crevice area are thought not to ignite before the ignition of the fuel-air mixture by the spark plug. Rather, the gas around the droplet increases rapidly after the start of combustion. Therefore, the temperature of the droplet also increases within the burning gas. If the droplet is not exhausted from the combustion chamber, this high temperature droplet will remain in the gasoline-air mixture in the next cycle. In the next section, the conditions of the droplet in the combustion chamber are estimated.

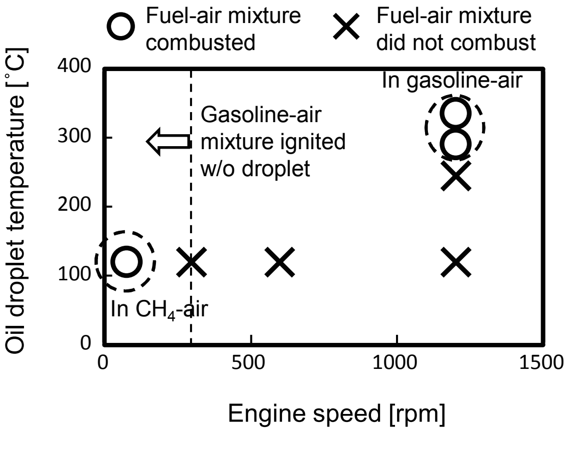

Fig. 10 Conditions of engine speed and oil droplet initiating combustion of fuel-air mixture, $d_0 > 100$ μm.

3. Numerical Analysis

3. 1 Numerical Analysis Method

Calculations were used to estimate the changes over time of the droplet diameter and the droplet temperature. It was assumed that the droplet is spherically symmetrical and has no temperature distribution in the liquid phase. The oil vapor concentration at the surface of the liquid was fixed using boundary conditions calculated from the saturated vapor pressure. The following equations were solved.

$$\frac{dT_d}{dt} = \frac{\frac{dQ}{dt} + L_v \frac{dm}{dt}}{V\rho_d C_{pd}} \qquad (1)$$

$$\frac{dm}{dt} = -\pi d \rho_d D sh \ln(1+B) \qquad (2)$$

T_d: Droplet temperature
Q: Heat transferred from gas phase to droplet
L_v: Latent heat of vaporization
m: Mass of droplet

V : Volume of droplet
ρ_d: Density of droplet
C_{pd}: Specific heat of droplet
d : Diameter of droplet
D: Diffusion coefficient
sh: Sherwood number
B : Transfer number

The components of the droplet were represented by the hydrocarbons shown in **Table 2** to determine the evaporation characteristics of the oil. The calculations started from the timing of an initial intake valve close (IVC) to the IVC of the next cycle at an engine speed of 1200 rpm. The gas pressure (P_g) was the value measured in the combustion cylinder when LSPI occurs in a boosted gasoline engine. The gas temperature (T_g) between the IVC and the timing of the exhaust valve open (EVO) was the average value in the cylinder calculated using the equation of state. From the EVO to the timing of the intake valve open (IVO), T_g was assumed to be constant and equal to the value at the EVO. When the intake valve opened, T_g was assumed to equal the intake gas temperature. The relative velocity of the gas to the droplet during the IVO was 20 m/s. During the other period, this value was 10 m/s.

3. 2 Numerical Results

Figure 11 shows the histories of T_g and the droplet temperature in the cases of d_0 = 60 μm and 500 μm at −118° ATDC. Here T_{d0} is 60°C, which is the same as the intake gas temperature. The droplet temperature gradually increases before the combustion of the mixture starts and increases more rapidly after the onset of combustion. In the case of d_0 = 60 μm, the oil droplet disappears at approximately 30° ATDC. In contrast, the oil droplet does not disappear and the droplet temperature increases gradually in the case of d_0 = 500 μm. After the IVO, the droplet temperature is decreased by the intake gas; therefore it has a value of 316°C at the IVC of the next cycle. The droplet diameter also becomes 380 μm.

Table 2 Components of a droplet in the calculation.

n-Octane (n-C_8H_{18})	12.2 mol%
n-Decane (n-$C_{10}H_{22}$)	8.5 mol%
n-Tetradecane (n-$C_{14}H_{30}$)	12.6 mol%
n-Hexadecane (n-$C_{16}H_{34}$)	22.5 mol%
n-Eicosane (n-$C_{20}H_{42}$)	34.1 mol%
n-Heptacosane (n-$C_{27}H_{56}$)	10.1 mol%

The droplet conditions were calculated by varying d_0 at T_{d0} = 60°C, and **Fig. 12** presents the calculated residual droplet conditions at the IVC after exposure to the combustion gases. Smaller droplets do not exist because they are evaporated prior to the IVC. The temperature of a droplet that does not disappear is higher than T_{d0}, and the temperature is over 300°C when the diameter is between 250 and 500 μm. Below 250 μm, the droplet temperature decreases as the diameter decreases. The droplet temperature increases significantly and the droplet diameter decreases drastically until the exhaust stroke. During the intake stroke, the droplet is rapidly cooled if the diameter is

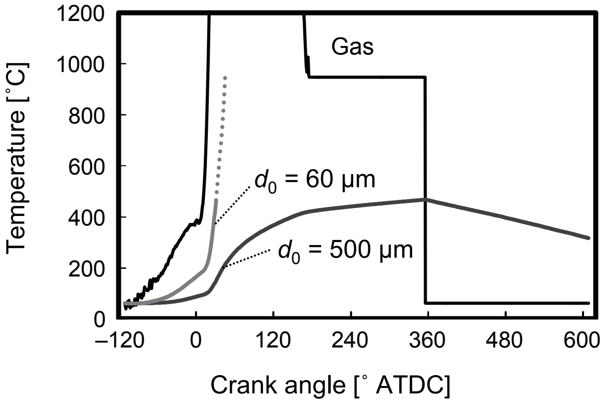

Fig. 11 Gas and calculated droplet temperature, T_{d0} = 60˚C.

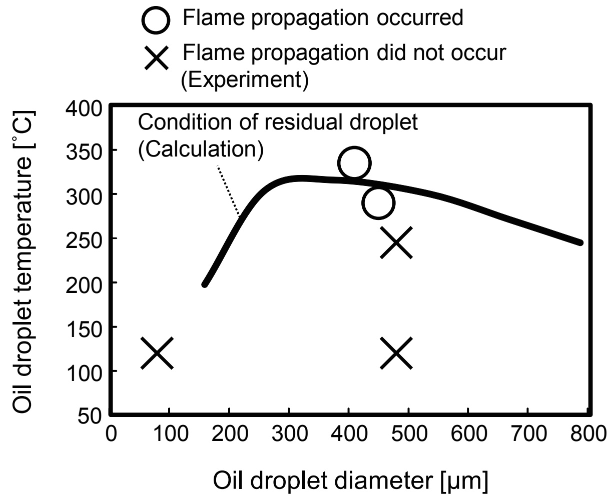

Fig. 12 Conditions of calculated residual droplet at next IVC and tested droplet.

small; therefore, the droplet temperature is lowered. Conversely, droplets larger than 500 μm also exhibit low temperatures because the droplet temperature increases slowly as the result of a large heat capacity. The droplet test conditions with t_{comp} = 25 ms are also represented in Fig. 12. Here, the circle symbols indicate flame propagation of the gasoline-air mixture initiated by the droplet, while the crosses show that flame propagation does not occur. The oil droplets for which conditions are almost the same as the calculated droplet conditions at the IVC of the next cycle initiate flame propagation. This result indicates that the oil droplet will trigger the combustion of the gasoline-air mixture if it is heated by combustion gases and not subsequently exhausted. This is thought to be one possible LSPI mechanism.

4. Conclusions

This study investigated the conditions under which a single oil droplet can initiate the combustion of the surrounding fuel-air mixture. The following conclusions can be drawn:

· The ignition delay of the oil droplet was reduced as the initial droplet diameter decreased and the initial droplet temperature increased, because evaporation is a factor controlling the ignition process. When the initial droplet temperature was over 250°C, the vaporized oil ignited earlier than the gasoline-air mixture. In this case, the combustion of the gasoline-air mixture was initiated by the oil droplet.

· In the case of a low compression speed, a low temperature oil droplet ignited. However, this ignition did not trigger the combustion of the gasoline-air mixture because the gasoline-air mixture ignited earlier than the oil droplet. When the ignitability of the fuel was lower, such as when using methane, the fuel-air mixture was ignited by the oil droplet.

· In automotive gasoline engines, an oil droplet immediately after release from the piston crevice area will not initiate the combustion of the fuel-air mixture because of the low droplet temperature. When the droplet is heated by residual combustion gases in the combustion chamber, however, the oil droplet temperature is increased to over 250°C. As a result, the droplet, if it remains in the cylinder, can potentially trigger the combustion of the fuel-air mixture in the subsequent cycle.

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Figs. 1, 2(a), 8, 11-12 and Tables 1-2
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Figs. 3-5 and 7
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Figs. 6, 9 and 10
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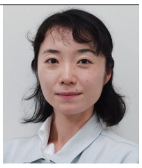
- Invention Award of JSME Tokai Branch, 2003
- JSME Medal for Outstanding Paper, 2003



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Academic Society:
- Society of Automotive Engineers of Japan

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