

An Investigation on the Ignition Characteristics of Lubricant Component Containing Fuel Droplets Using Rapid Compression and Expansion Machine

Masaharu Kassai, Taisuke Shiraishi, and Toru Noda
Nissan Motor Co., Ltd.

Mamoru Hirabe, Yoshiki Wakabayashi, Jin Kusaka, and Yasuhiro Daisho
Waseda University

ABSTRACT

With the development of downsized spark ignition (SI) engines, low-speed pre-ignition (LSPI) has been observed more frequently as an abnormal combustion phenomenon, and there is a critical need to solve this issue. It has been acknowledged that LSPI is not directly triggered by autoignition of the fuel, but by some other material with a short ignition delay time. It was previously reported that LSPI can be caused by droplets of lubricant oil intermixed with the fuel.

In this work, the ignition behavior of lubricant component containing fuel droplets was experimentally investigated by using a constant volume chamber (CVC) and a rapid compression and expansion machine (RCEM), which enable visualization of the combustion process in the cylinder. Various combinations of fuel compositions for the ambient fuel-air mixture and fractions of base oil/metallic additives/fuel for droplets were tested.

CVC results confirmed the high ignitability of lubricant component containing fuel droplets in pre-heated air, which was responsible for the early timing of LSPI. RCEM results also revealed the high ignitability of lubricant component containing fuel droplets in the premixed fuel/air mixture. Stochastic occurrence of ignition induced by fuel droplets was also observed, particularly under a condition of a small lubricant oil fraction.

Finally, the contribution of base oil and metallic additives to the ignitability (delay times and probabilities) of droplets was separately evaluated to understand the fundamental mechanism involved. Results confirmed that the base oil itself can promote the high ignitability of fuel droplets and that metallic additives can also additionally promote or inhibit the ignitability of droplets in the premixed fuel-air mixture.

CITATION: Kassai, M., Shiraishi, T., Noda, T., Hirabe, M. et al., "An Investigation on the Ignition Characteristics of Lubricant Component Containing Fuel Droplets Using Rapid Compression and Expansion Machine," *SAE Int. J. Fuels Lubr.* 9(3):2016, doi:10.4271/2016-01-2168.

INTRODUCTION

In recent years, global warming and depletion of oil resources as well as air quality problems have become more serious. For automotive engines, further reduction of CO₂ emissions and fuel consumption by achieving higher efficiency is rigorously required. With this motivation, the concept of engine downsizing has been the focus of much attention in recent years and has become more widespread.

The concept of downsizing is to achieve higher efficiency by reducing engine displacement and simultaneously making up for the loss of torque/power via turbocharging. Generally, downsized engines adopt gasoline direct injection (GDI) for mitigating knocking by the mixture cooling effect so that the downsizing ratio and compression ratio can be set higher.

With the development of highly turbocharged direct injection gasoline engines, low-speed pre-ignition (LSPI) has been observed more frequently as an abnormal combustion phenomenon. LSPI is known to induce autoignition of decisively stronger intensity compared with normal knocking. Thus, it is regarded as an important technical challenge to reconcile high torque output with sufficient suppression of LSPI under conditions of low engine speed and high boost pressure.

Two typical types of LSPI behavior have been reported and are well known. First, it occurs suddenly under normal steady-state operation. Second, once an abnormal LSPI cycle occurs, subsequent LSPI cycles will follow intermittently and finally combustion will return to normal cycles [1].

For the second type of behavior, a mechanism has been reported and clarified by several researchers. It has been reported based on precise visualization that solid particles generated or exfoliated by pressure oscillations in the first abnormal cycle can subsequently pre-ignite due to self-heating in a normal cycle [2-3]. Artificial triggering of subsequent LSPI by a significant spark timing advance to prove the mechanism has also been reported [2, 3, 4]. Further, the authors confirmed the dependency of subsequent LSPI events on normal operation time [5]. These results confirmed that subsequent LSPI is induced and triggered by continuous operation and the first LSPI cycle.

On the other hand, many possible mechanism hypotheses have been reported for the sudden occurrence of the first LSPI cycle: droplets [1], deposits [4, 6], and blow-by oil re-flux [7], among others. To validate these mechanism hypotheses, fundamental investigations on the ignitability of pre-ignition sources have been conducted and reported [8, 9, 10].

In this work, we focused on lubricant oil containing droplets as a candidate of pre-ignition sources. The mechanism hypothesis examined is shown in Figure 1. The objective of this investigation was to observe and clarify the mechanism causing droplet ignition and subsequent flame propagation. LSPI sensitivity to the base oil or metallic additives as lubricant oil components in particular has been reported [11, 12, 13]. We tried to understand the fundamental mechanism of this sensitivity by separating the effects of each parameter.

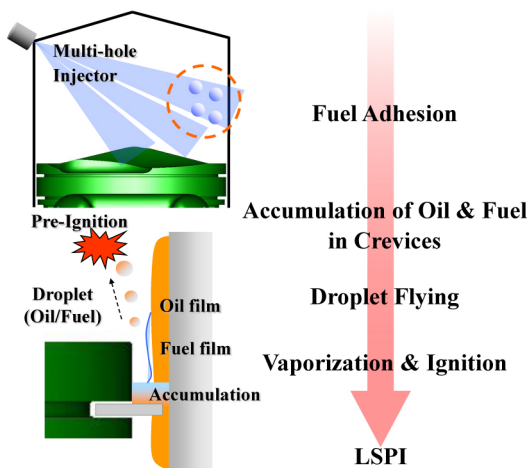


Fig. 1. Mechanism hypothesis of droplets triggered LSPI

EXPERIMENTAL METHODOLOGIES

Constant Volume Chamber (CVC)

Figure 2 shows the experimental CVC apparatus used in this investigation. A vacuum pump and supply lines of C_2H_4 (ethylene), O_2 and N_2 from cylinders are connected to the chamber. Each gas can be charged under controlled pressure. Pre-combustion of a lean

premixed C_2H_4 /air mixture can raise the temperature and pressure of the ambient gas with residual O_2 . The sample, lubricant oil and fuel mixture are directly injected with a single-hole diesel injector into the pre-heated and pre-compressed chamber. Ignition and combustion of the fuel spray were observed and recorded by a high-speed camera (MEMRECAM GX-8, NAC Image Technology) through a glass window.

Although ambient conditions should be equivalent to those of the pre-ignition timing (before compression TDC) in highly turbocharged downsized engines, it was impossible to set exactly the same conditions from the standpoint of safety. Thus, the temperature and O_2 density, known as the dominant parameters of ignition, were selected to be equivalent to those of actual engines, as shown in Figure 3. These conditions are equivalent to -45/-30/-20/-10 deg. ATDC in the compression stroke under turbocharging. In addition to these basic conditions, a/b/c/d conditions with different O_2 density or temperature were set to supplement condition sensitivities.

Ignitability tests of fuel spray with various mixture ratios of lubricant oil and fuel were conducted as shown in Table 1. In the CVC experiments, only commercial oil was tested. Under all conditions, the density in the chamber was set to 12 kg/m^3 . The pressure difference between the sample and ambient gas was kept constant at 30 MPa. The amount of fuel injected was controlled to 1 mg.

Rapid Compression and Expansion Machine (RCEM)

CVC experiments enabled us to evaluate the ignitability of fuel/oil droplets under pre-heated ambient gas with residual O_2 .

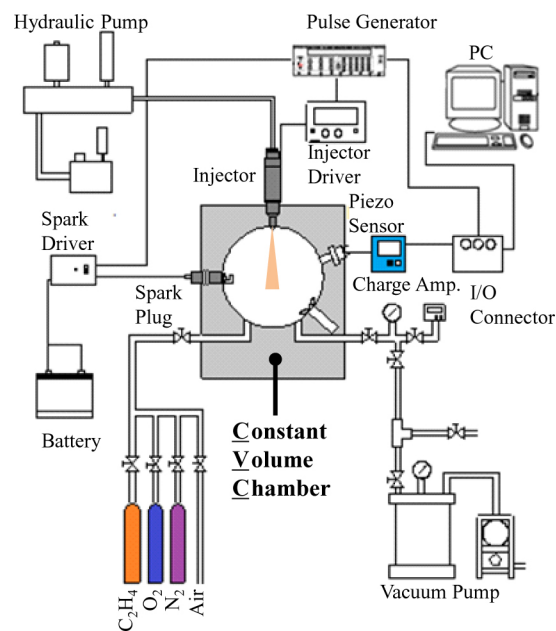


Fig. 2. Experimental schematic of constant volume chamber (CVC)

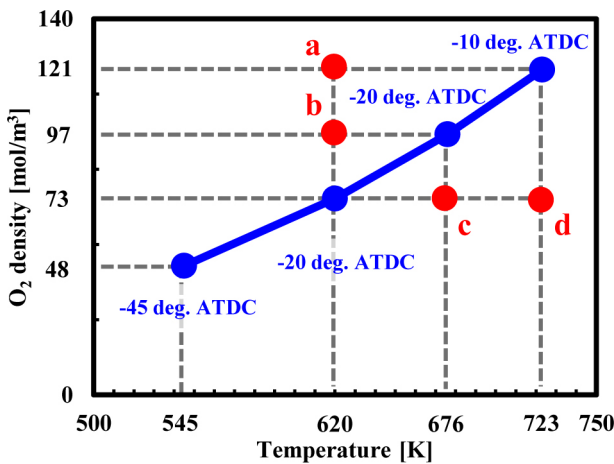
Fig. 3. O₂ density and temperature conditions of CVC

Table 1. Experimental conditions of CVC tests

Mixing Ratio of Lubricant Oil	[wt %]	0, 20, 50, 60, 80, 100
Pres. Difference (fuel ⇌ ambient)	[MPa]	30
Amount of Injection	[mg]	1.0
Ambient Density	[kg/m ³]	12
Camera Flame Rate	[fps]	10000

However, the actual pre-ignition event was expected to be ignition of fuel/oil droplets in the fuel/air mixture. For that reason, we decided to use a rapid compression and expansion machine (RCEM) to observe the ignition of fuel/oil droplets and subsequent flame propagation in the fuel/air mixture.

Figure 4 shows a schematic of the RCEM. The basic RCEM specifications are shown in Table 2. This RCEM can simulate the piston motion of a reciprocating engine's compression and expansion strokes with its cam profile. The descending cam (total weight = 180 kg) moves the piston along the cam profile one time. Compression ratio settings can be changed easily by changing the cylinder head position.

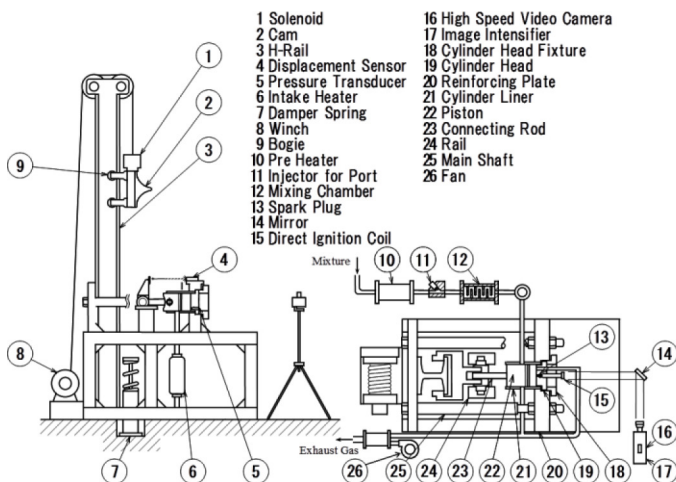


Fig. 4. Experimental schematic of RCEM

Table 2. Basic specifications of RCEM

Bore	[mm]	125
Stroke	[mm]	140
Displacement	[cc]	1718

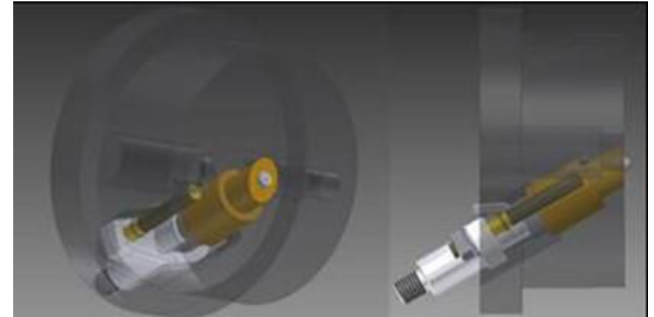


Fig. 5. Cylinder head and injector mounting layout

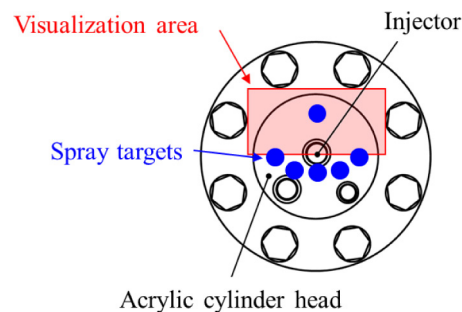


Fig. 6. Geometrical layout of spray direction and visualization area

Table 3. Experimental conditions of RCEM with different fuels

Fuel Type	[-]	Methane Mixture	PRF Mixture
Initial Gas Pressure	[kPa]	25	25
Initial Gas Temperature	[K]	383.15	383.15
Compression Ratio	[-]	14 : 1	10.5 : 1
Engine Speed	[rpm]	800	800
Equivalence Ratio	[-]	1.0	1.0

A transparent cylinder head made from polished acrylic was used to facilitate visualization of in-cylinder phenomena. The ignition kernels of fuel/oil droplets and subsequent flame propagation were observed using images obtained with the high-speed camera mentioned earlier. Both the visualized images and pressure measurements allow quantitative evaluation of ignition delay times.

For the injection of the oil/fuel mixture, we prepared a special six-hole, solenoid-driven DI injector for gasoline engines. To avoid wetting of the spray stream on the piston crown surface, the injector was mounted at an inclined angle. Targets of the spray streams were also optimized. One stream for observation was designed to penetrate freely in the visualization area without wetting any wall, while the other five streams penetrated toward the outside of the visualization

area. Figure 5 shows a schematic of the cylinder head and injector mounting design. Figure 6 shows the geometrical relation between the injector streams and the visualization area.

Table 3 shows the initial conditions and compression ratio settings of the RCEM tests. The difference in the compression ratio settings between methane (120 RON) and the primary reference fuel (PRF, 90-100 RON) was derived from the autoignitability of the premixed fuel/air mixture. Due to the piston speed limitation of the RCEM (800 rpm), there was a risk of compression ignition of the entire mixture. To avoid that, the base conditions were set on the safe side at lower temperature and pressure levels.

Lubricant Oil Properties and Test Conditions

Table 4 shows the properties of commercial oil A that was used for both CVC and RCEM experiments. Table 5 shows the properties of base oil B that was used only for RCEM experiments. In addition to the commercial oil and base oil, the effects of calcium sulphonate and ZnDTP, typical metallic additives, on fuel droplet ignition characteristics were also examined. Fuels for the premixed mixture were methane and PRF. Iso-octane alone was used as the fuel for droplets. Various combinations of ambient conditions and droplet compositions were tested in the CVC and RCEM experiments. Table 6 summarizes all the combinations and the test conditions.

Table 4. Properties of commercial oil A

Name	[-]	Commercial Oil A
Grade	[-]	SM/GF-4
Base Oil Group	[-]	Gr. III
SAE Viscosity Grade	[-]	5W-30
Density (15 deg. C)	[kg/m ³]	0.8414
Kinetic Viscosity	100 deg. C	[mm ² /s] 9.808
	40 deg. C	[mm ² /s] 47.15
Viscosity Index	[-]	200

Table 5. Properties of base oil B

Name	[-]	Base Oil B
Base Oil Group	[-]	Gr. III
Density (15 deg. C)	[kg/m ³]	0.886
Kinetic Viscosity	100 deg. C	[mm ² /s] 10.8
	40 deg. C	[mm ² /s] 93.9
Viscosity Index	[-]	97

RESULT AND DISCUSSION

Test 1: Market Oil Ignitability in CVC

The ignitability of the commercial oil and fuel mixture with various mixture ratios was first experimentally evaluated in the CVC. The commercial oil or oil/fuel droplets were injected into the pre-heated ambient gas with residual O₂ in the CVC.

Figure 7 shows examples of the visualized ignition and subsequent combustion of oil/fuel mixture droplets under a condition equivalent to -10 deg. ATDC of a downsized engine. The results for only iso-octane (oil ratio = 0%) were excluded because no ignition was observed at all. The ignition and combustion of oil containing droplets produced a bright red light, which became brighter with a higher oil ratio. Presumably, it was caused by soot radiation or flame reaction of metallic detergents in the lubricant oil.

Table 7 shows the obtained ignition delay times. A higher oil ratio led to a shorter ignition delay. The absolute values of the extremely short ignition delay times are thought to be relevant for the pre-ignition source of LSPI. Assuming 1600 rpm as a typical engine speed for the occurrence of LSPI, a short ignition delay time of around 1.0 ms is equivalent to roughly 10 deg. CA. This is probably short enough for ignition soon after droplets begin flying in the compression stroke [5].

Table 6. Experimental conditions of CVC and RCEM: Combinations of ambient conditions and droplet composition

Case No.	Method.	Ambient Conditions		Droplet Composition					Droplets Injection Settings		
		Fuel Type	Comp. Ratio	Fuel	Com. Oil A	Base Oil B	Calcium	ZnDTP	Timing	Inj. Pres.	Amount
[-]	[-]	[-]	[-]	[wt %]	[wt %]	[wt %]	[wt %]	[wt %]	[deg. ATDC]	[MPa]	[mg]
Test 1	CVC	Air Only	-	100 RON (Iso-octane)	0 - 100	N/A	N/A	N/A	See Table 1		
Test 2	RCEM	Methane	14 : 1		0 - 8	N/A	N/A	N/A	-28	3.8	0.5
Test 3	RCEM	Methane	14 : 1		N/A	1 - 4	N/A	N/A	-28	3.8	0.5
Test 4	RCEM	Methane	14 : 1		N/A	2	0 - 2	N/A	-28	3.8	0.5
Test 5	RCEM	Methane	14 : 1		N/A	N/A	0 - 0.39	N/A	-28	3.8	0.5
Test 6	RCEM	95 RON (PRF)	10.5 : 1		N/A	N/A	0 - 1.57	N/A	-22	3.8	0.5
Test 7	RCEM	90 - 100 RON (PRF)	10.5 : 1		N/A	N/A	0.784	N/A	-22	3.8	0.5
Test 8	RCEM	90 RON (PRF)	10.5 : 1		N/A	N/A	0.784	0 - 0.3	-22	3.8	0.5