

Visualization and Analysis of LSPI Mechanism Caused by Oil Droplet, Particle and Deposit in Highly Boosted SI Combustion in Low Speed Range

Tatsuya Kuboyama, Yasuo Moriyoshi, and Koji Morikawa
Chiba Univ.

ABSTRACT

In this study, in order to clarify the mechanism of preignition occurrence in highly boosted SI engine at low speed and high load operating conditions, direct photography of preignition events and light induced fluorescence imaging of lubricant oil droplets during preignition cycles were applied. An endoscope was attached to the cylinder head of the modified production engine. Preignition events were captured using high-speed video camera through the endoscope. As a result, several types of preignition sources could be found. Preignition caused by glowing particles and deposit fragments could be observed by direct photography. Luminous flame was observed around the piston crevice area during the exhaust stroke of preignition cycles. This implies that the lubricant oil or mixture of oil and liquid fuel which is accumulated in the piston crevice area burns under low oxygen condition, and that the glowing particles which induce preignition would be produced in the oil combustion during the expansion stroke. Preignition induced by a lubricant oil droplet ignition was probably captured using fluorescence technique. Through the investigations, preignition which occurs at the piston crevice area was often observed. It was also found that preignition event often terminated in a single cycle in the present study and hardly occurred in the sequential manner including normal SI combustion as has been frequently reported in the previous studies. This is probably because a scavenging efficiency in the engine operating condition in this experiment is high. In the conventional boosted gasoline engine, an exhaust pressure increases, and some of the particles generated during first preignition cycle are not scavenged and remain inside the cylinder. The residual particles are heated during the subsequent combustion cycle and induce the preignition again. Preignition event continues until the residual particles are consumed. This would be one of the possible mechanism of the sequential preignition occurrence.

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INTRODUCTION

Highly boosted downsized SI gasoline engines have been widely applied to improve fuel efficiency. In order to achieve higher level of boosted operation, suppressions of knocking and preignition at low speed and high load conditions are necessary. Especially, to clarify the mechanism of preignition initiation is important because preignition induces knocking with strong in-cylinder pressure oscillation causes heavy engine damage. However, this low-speed preignition has stochastic and infrequent nature, it is difficult to find the source of this problem. In recent years, many investigations about low speed preignition have been conducted. Especially, direct observations using optical visualization techniques have provided a lot of useful information to understand this phenomenon.

It have been reported that abnormal ignition of droplets of lubricant oil, and ignition of mixture induced by hot deposit particles have been found as possible sources of the low-speed preignition[1]-[7]. Dahnz et al. [1] systematically conducted numerical and experimental investigations to find the source of the preignition. As a result, they pointed out that the ignition of the droplets of lubricant oil diluted by the fuel is the most possible source of the low-speed preignition. They also reported that preignition occurs in series intermittently

including normal SI combustion and that about 75 % of preignition occurred within sequences of 2 to 7 preignitions. Okada et al. [5] carried out high-speed imaging of preignition events and concluded that the deposit fragments detached from the wall inside the cylinder initiates preignition. Lauer et al.[6] report that both solid particles and oil droplets could be the source of preignition based on their visualization investigation. Döehler et al. also carried out visualization of preignition and showed one possible mechanism of sequential manner of preignition. They claim that preignition following to the former preignition is driven by particles dislodged from the combustion chamber surface[7].

The authors comprehensively investigated the mechanism of preignition in highly boosted SI engines. An experimental investigation to find the effects of engine operating parameters on preignition was carried out using a production four-cylinder engine[8]. Also, a numerical study was carried out to identify the possible source of preignition and the mechanism of preignition initiation[9]. In this study, to clarify the mechanism of preignition occurrence in highly boosted SI engine, direct photography of preignition events and light induced fluorescence imaging of

lubricant oil droplets during preignition cycles were carried out. Also, the mechanism of the sequential manner of low speed preignition occurrence is discussed.

EXPERIMENTAL SETUP

Test Engine and Conditions

To clarify the cause of preignition under low speed and high load engine operating conditions in a boosted gasoline engine, preignition event was visualized using a modified production four-cylinder engine.

Table 1 shows some of the main specifications of the test engine. The engine has a bore of 79.7 mm and a stroke of 81.1 mm. A displacement volume of the engine is 404 cm³ per cylinder and a compression is 9.49. In this experiment, only one of the four cylinders was activated, and the others were deactivated by stopping fuel injection, spark ignition and valve actuation. An endoscopic technique was applied to visualize in-cylinder combustion processes including low speed preignition. An electrically driven lysholm supercharger was used to realize highly boosted operating condition.

Table 1. Specifications of the test engine

Engine Type		Four-stroke four-cylinder
Bore × Stroke		Φ79.7mm × 81.1 mm
Displacement		404.2 cm ³
Compression Ratio		9.49
Fuel supply system		Direct injection
Boosting system		Electrically driven lysholm
Valve Timing (at 1mm lift)	Intake	11°ATDC
		59°ABDC
	Exhaust	13°BBDC
		27°ATDC

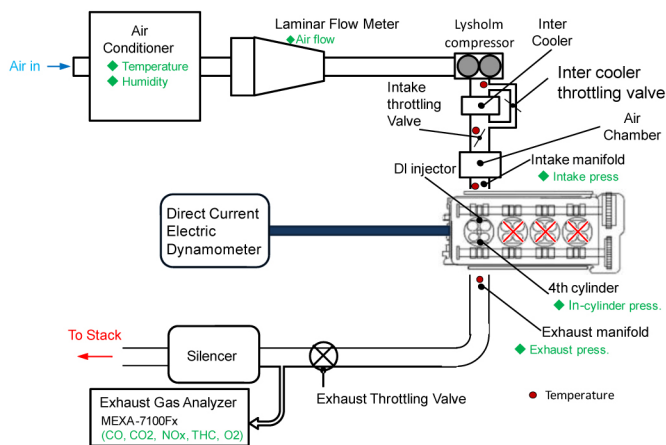


Figure 1. Experimental set up

Figure 1 shows experimental set up. A piezoelectric pressure transducer (Kistler Type 6043A) was installed for in-cylinder pressure measurement. Piezo-resistive pressure transducers (Kistler 6041B for intake pressure and 4049A for exhaust pressure) were mounted in the exhaust and the intake manifolds of the activated cylinder for measurement of the exhaust and intake pressure pulsations. The pressure transducers for intake and exhaust pressure can measure absolute pressure. All the indicated pressure data including indicated mean effective pressure (IMEP), apparent heat release rate and combustion phase were computed from the pressure trace of each cycle measured with 0.1 degree in crank angle interval. The exhaust emissions, which are CO, CO₂, THC, NO_x and O₂ levels, were measured by using a HORIBA MEXA-7100FX. In-cylinder gas temperature, residual gas fraction were estimated numerically using the 1-D engine cycle analysis called TPA (Three Pressure Analysis) supported by the simulation code, GT-Power. The boundary conditions for intake and exhaust in the estimations were given by experiments.

Table 2 shows experimental conditions. Engine speed was fixed at 1750 rpm through the experiment. Temperature and relative humidity of air aspirated by supercharger were set at 25 °C and 50 % using an air conditioner. A boost pressure was set at around 220 kPa (abs.) which corresponds to about 2.4 MPa of IMEP. A boosted air was cooled using a water-cooled type inter cooler and the intake air temperature monitored at intake manifold was fixed at 35 °C through the experiment.

Cooling water temperature has large impact on preignition frequency. According to a preliminary experiment conducted before the present work, preignition occurs with increased frequency with decreasing cooling water temperature[8]. Based on the preliminary result, to increase preignition occurrence frequency, a cooling water temperature measured at engine outlet was set at 65 °C, which is relatively lower than conventional engine operating condition.

For fuel injection, a direct injection system normally attached to the commercial engine was used. Commercially available premium gasoline (RON 100) was injected with an injection pressure of 10 MPa during intake stroke. Fuel injection timing was fixed at 150 degrees after TDC during intake stroke. This injection timing brought preignition with higher frequency in the preliminary experiment[8]. An air-fuel ratio (A/F) measured at exhaust manifold was fixed 14.6. A spark ignition timing was set at 2deg. ATDC or 4deg. ATDC.

Table 2. Experimental conditions

Engine speed	1750 rpm
Target load	IMEP 2.2~2.4 MPa
Intake pressure (absolute)	210~220 kPa
Intake temperature	308K
Ignition timing	2 deg.ATDC, 4 deg.ATDC
Fuel injection timing	150 deg.ATDC (Intake stroke)
Fuel injection pressure	10 MPa
Fuel	Premium gasoline (RON 100)

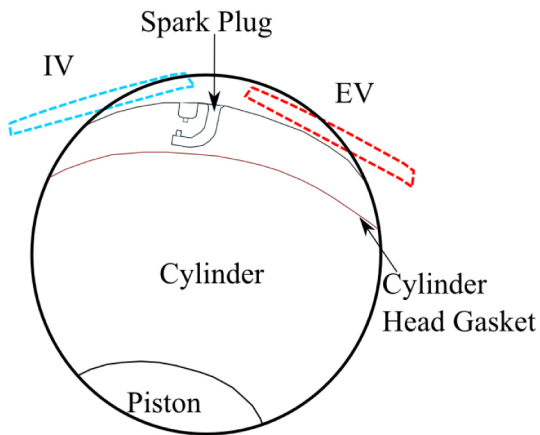


Figure 2. Visualization field through the endoscope attached to the cylinder head (at BDC)

Visualization of Preignition

High speed direct photography using an endoscope (Karl Storz REF88370AX) and high speed digital camera (Photron SA-X and SA-X2) was examined to visualize preignition events. The endoscope was attached to the cylinder head of the test engine. Viewable field through the endoscope is depicted in Figure 2. In addition to the direct photography of preignition, light induced fluorescence imaging technique was applied to visualize lubricant oil droplet inside the cylinder because oil droplet ignition has been considered as one of the possible cause of preignition[1], [6]. Coumarin-6 was added into the lubricant oil as a fluorescence agent. A xenon lamp (Hamamatsu photonics, L9588-06A) was used as a UV excitation light source. The incident light was guided into the cylinder from near the spark plug through an optical fiber light guide attached on the cylinder head. In some cases, incident light from external source was guided into the cylinder coaxially along with the optical axis of the endoscope.

RESULT AND DISCUSSION

Causes of Preignition and Characteristics of Preignition Cycles

Preignition Caused by Hot Particles

Deposit particle or flakes detached from the wall inside the cylinder and lubricant oil droplets have been reported as possible causes of preignition[1, 5, 6, 7]. In the present study, preignition events initiated by mixture abnormal ignition induced by hot particles, detached deposits and preignition occurred around the piston crevice could be observed. Also, it would appear that preignition initiated by oil droplet ignition could be obtained by the fluorescence imaging.

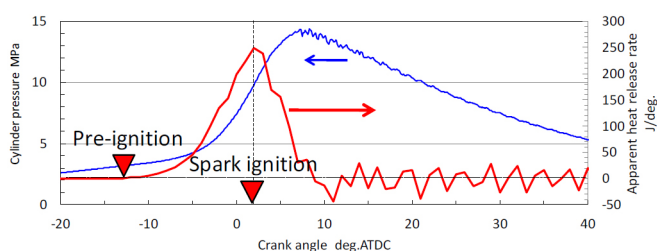


Figure 3.

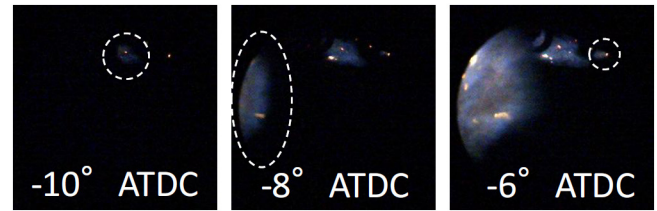


Figure 3. (cont.) In-cylinder pressure trace, apparent rate of heat release and direct photographs during preignition cycle induced by glowing particles

In Figure 3, in-cylinder pressure trace and apparent heat release rate are indicated with direct photographs during preignition initiated by the hot particles. In this cycle, some glowing particles were observed even during early stage of compression stroke, and these glowing particles induced preignition before spark ignition timing. As can be seen in the heat release rate in the figure, heat release was initiated at about -12 deg. ATDC which is far earlier than the spark ignition timing set at 2 deg. ATDC. Once preignition occurs, though a relatively steep increase in in-cylinder pressure can be seen, a pressure rise rate of the preignition cycle seems to be less than that of compression ignition combustion cycle like HCCI combustion. This implies that the preignition is distinct from the abnormal ignition of bulk gas, but would be the early local abnormal ignition followed by flame propagation. In this cycle, three local preignition could be observed. From the direct photographs at crank angle of -10 deg. ATDC, it can be seen that a preignition is induced by glowing particle, and after that, the flame propagation is initiated. At -8 deg. ATDC, flame propagation probably initiated by the other preignition source can be observed. Also, at -6 deg. ATDC, third preignition induced by another glowing particle could be captured. As is shown in this cycle, sometimes preignitions induced by a number of sources.

In Figure 4, high-speed monochrome photographs of preignition induced by detached deposit flakes are depicted. In this case, an external light source was used to observe in-cylinder situation before combustion. The incident light from external source was guided into the cylinder coaxially along with the optical axis of the endoscope. It should be noted that a round-shaped strong image in these photographs is light reflection of incident light. Photographs shown in Figures 4(a) were taken during intake stroke, and those shown in Figures 4(b) were taken during compression stroke. From Figures 4(a), it can be seen that deposit fragments detached from the chamber wall during the previous cycle still remains in the cylinder and are floating. In the photograph at -11 deg. ATDC in Figure 4(b), it is depicted that preignition is induced by one of the residual deposit fragments around spark plug.

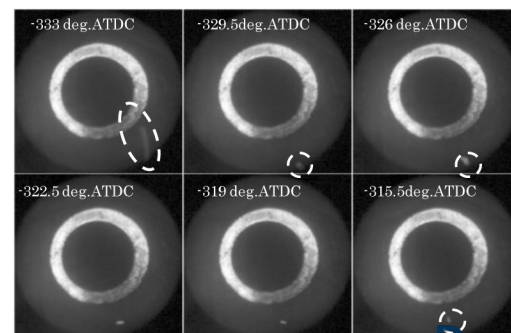


Figure 4 (a). High speed photographs taken during intake stroke of the cycle in which pre-ignition induced by deposits detached from the chamber wall.