

Study of Low-Speed Pre-Ignition in Boosted Spark Ignition Engine

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ABSTRACT

This paper analyzes low-speed pre-ignition (LSPI), a sudden pre-ignition phenomenon that occurs in downsized boosted gasoline engines in low engine speed high-load operation regions.

This research visualized the in-cylinder state before the start of LSPI combustion and observed the behavior of particles, which are thought to be the ignition source. The research also analyzed pre-ignition by injecting deposit flakes and other combustible particulate substances into the combustion chamber. The analysis found that these particles require at least two combustion cycles to reach a glowing state that forms an ignition source. As a result, deposits peeling from combustion chamber walls were identified as a new mechanism causing pre-ignition.

Additionally, results also suggested that the well-known phenomenon in which the LSPI frequency rises in accordance with greater oil dilution may also be explained by an increase in deposit generation.

CITATION: Okada, Y., Miyashita, S., Izumi, Y., and Hayakawa, Y., "Study of Low-Speed Pre-Ignition in Boosted Spark Ignition Engine," *SAE Int. J. Engines* 7(2):2014, doi:10.4271/2014-01-1218.

INTRODUCTION

More vehicles are being fitted with downsized boosted gasoline engines to help improve fuel economy. However, in these engines, improvements in torque at low engine speeds are restricted by a sudden pre-ignition phenomenon called low-speed pre-ignition (LSPI), which occurs in low engine speed high-load engine operation regions. Despite much research, the source of LSPI and the ignition mechanism have yet to be fully identified.

The LSPI phenomenon targeted in this research generates very large cylinder pressures suddenly and without any preceding phenomena. As far as can be observed from in-cylinder pressure waveforms, combustion due to this pre-ignition phenomenon is caused by an ignition source somewhere in the combustion chamber, begins before the spark ignition timing, and is not a self-ignition phenomenon of the whole mixture. Optical investigations have found that the location of this ignition source is randomly distributed throughout the combustion chamber volume [1, 2, 3].

Suggestions for possible ignition sources that exist throughout the combustion chamber include oil droplets and deposit peelings [4][5]. According to the ignition mechanism proposed by Willand et al. [4], oil droplets are brought into the combustion chamber by crankcase ventilation and self-ignite during the compression stroke. Furthermore, deposits that peel from the cylinder head and piston reach the same temperature as the combustion gas during combustion and are maintained at a high temperature in accordance with their thermal capacity. They form a pre-ignition combustion source early in the next combustion cycle.

In contrast, oil dilution has been suggested as a key characteristic affecting this phenomenon. The amount and evaporation characteristics of fuel impinging the cylinder liner, as well as the temperature of the liner wall have a correlation with the frequency of pre-ignition. Research has found that greater oil dilution increases the pre-ignition frequency [1][2]. Other research has also discovered that the pre-ignition frequency is greatly affected by the properties of the oil [2][6]. The hypothesis illustrated in Fig. 1, which was suggested by Dahnz et al., has been widely accepted as a mechanism that

neatly explains this oil effect [1]. Droplets from the oil film on the cylinder liner wall are scattered inside the combustion chamber by the action of the piston. As this oil dilution advances, the viscosity of the oil film decreases, increasing the droplet scattering rate. As a result, the frequency of pre-ignition also increases. The correlation with oil properties has also been described. For example, Takeuchi et al. reported a correlation between the pre-ignition frequency and the oil ignition temperature in high-pressure fields [6].

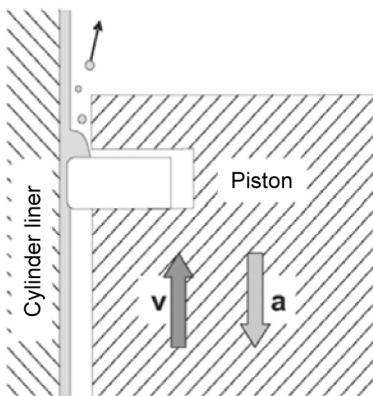


Figure 1. Release of oil droplets from top land [1].

However, oil droplets scattering from the cylinder liner wall and self-ignition caused by oil or a mixture of oil and fuel have yet to be verified in an actual engine. The latest numerical calculations suggest that oil or oil/fuel droplets do not reach the stage of self-ignition before the end of the compression stroke [7]. This research resolves this issue by attributing the cause of pre-ignition to the self-ignition of a substance originating from the interaction between the oil and the fuel spray. This substance is probably not an original part of the fuel or oil and may be generated inside the combustion chamber by incomplete combustion. This substance must have an extremely short ignition delay time to act as a pre-ignition combustion source.

Although empirical evidence for oil droplets as the source of self-ignition is not yet confirmed, Ando et al. confirmed that the injection of deposits into the combustion chamber causes pre-ignition in low engine speed high-load engine operation regions [3]. Therefore, the research described below used visualization technology to further clarify the phenomena in the combustion chamber when pre-ignition occurs. It also analyzed these phenomena in more detail by identifying the required conditions for substances to generate pre-ignition, using a system that injects particles into the combustion chamber. As a result, a new mechanism for pre-ignition was identified that alters the conventional hypothesis for the generation of pre-ignition.

OUTLINE OF PHENOMENON

Figure 2 shows the cylinder pressure when LSPI occurs. Unlike conventional pre-ignition, which is caused by hot surfaces of the spark plug and the like, LSPI greatly advances the ignition

timing suddenly and without any preceding phenomena, and cannot be controlled through the heat range of the spark plug or by adjusting the ignition timing [4][8].

Figure 3 shows the typical occurrence pattern of LSPIs. The graph in Fig. 3(a) shows the peak pressure value for one cylinder over 4,500 cycles (approximately 300 seconds). Figure 3(b) shows an enlarged view of the pre-ignition that occurred suddenly just after approximately 600 cycles. Pre-ignition occurs five times in every other cycle and then ceases. This series of phenomena is referred to as one sequence and several sequences occur over ten thousand cycles. LSPI occurs at this constant low frequency rate. This characteristic pattern has been the subject of a large number of reports [1][2][5][8] and is considered to be a fundamental characteristic of this phenomenon. In other words, an ignition source and process must be identified that explains this characteristic.

Other typical characteristics of this phenomenon include high sensitivity to the air-fuel (A/F) ratio. In this case, a rich mixture greatly reduces the frequency of pre-ignition [2][10].

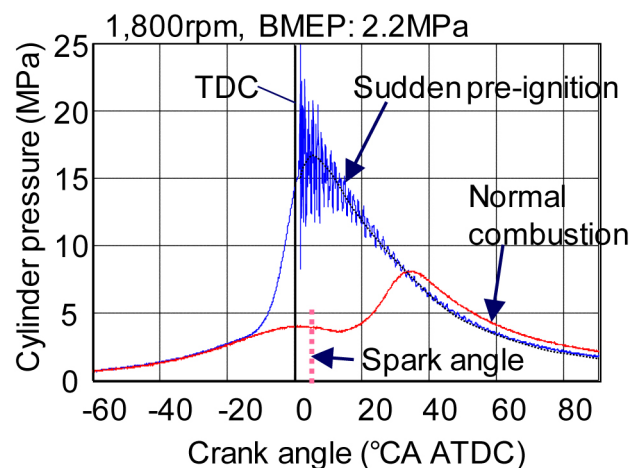


Figure 2. Cylinder pressure of LSPI.

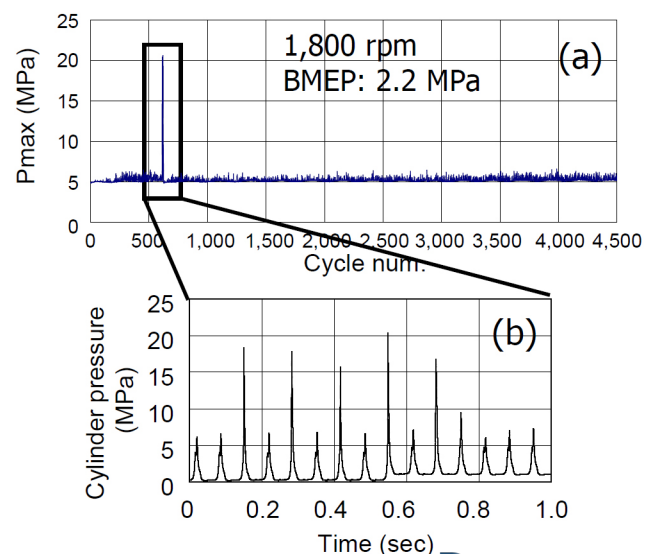


Figure 3. Typical sequence of LSPI.

TEST ENGINE

This research used an inline 4-cylinder boosted gasoline test engine. Table 1 shows the main test engine specifications and test conditions.

Table 1. Test engine specifications.

Engine type	GDI
Displacement	1997 cc
Compression ratio	10:1
Fuel	Gasoline (RON 99.5)
Engine speed	1,800 rpm
Load (BMEP)	2.2 MPa
Air-fuel ratio	14.6 (stoichiometric)
Coolant temperature	90 deg.C
Oil temperature	90 deg.C
Intake air temperature	25 deg.C
Air temp. after charge air cooler	45 deg.C

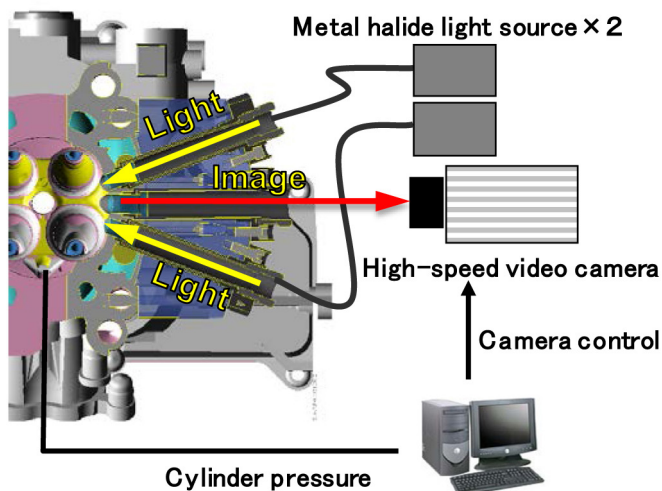


Figure 4. Visualization apparatus.

Figure 4 shows the visualization apparatus that was set up to observe the inside of the cylinder based on the engine described in Table 1. The purpose of this apparatus was to obtain a more detailed understanding of the in-cylinder phenomena when pre-ignition occurs. The apparatus was used to visualize the #4 cylinder. As shown in the figure, three windows were provided in the cylinder head. Two were used for light sources, which enabled clear identification of the phenomena in the combustion chamber before the start of combustion. The effective diameters of the observation and light-source windows were 12 and 10 mm, respectively. In this test, images were obtained through the central observation window using a high-speed video camera (the Memrecam GX-1 manufactured by NAC Image Technology, Inc. that has a frame rate of 10,000 frames per second). Sapphire windows were used and the windows at each end were concave. As shown in Fig. 5, virtually the whole area inside the chamber was visible through the observation window.

The observation system was configured to detect pre-ignition from the cylinder pressure and record images over five cycles starting one cycle before the pre-ignition occurrence.

Figure 6 shows the system that was constructed to inject deposits and various substances as ignition sources into the combustion chamber. The injected substances are the various types of materials which described in detail later. This deposit injection system was installed at the intake manifold and injects deposits placed in advance in a deposit chamber into the combustion chamber using air boosted to a pressure 30 kPa above the intake manifold pressure.

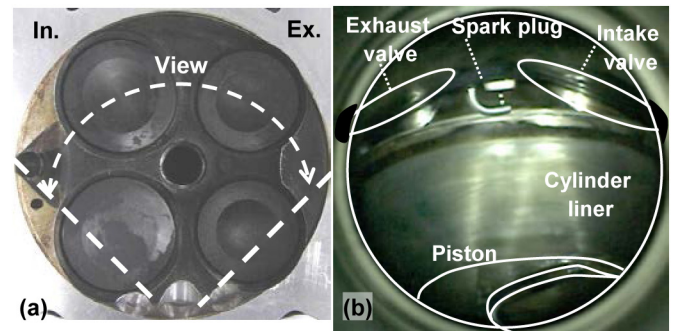


Figure 5. Observation area.

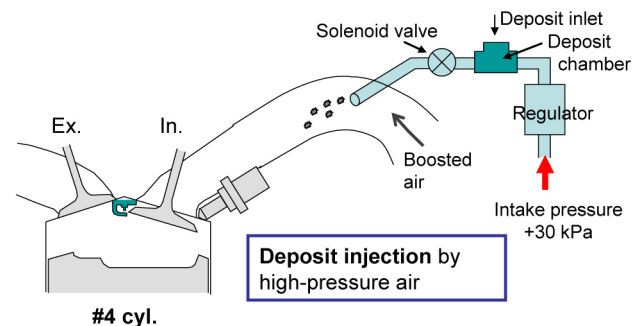


Figure 6. Deposit injection system.

VISUALIZATION OBSERVATION RESULTS

First, naturally occurring LSPI was visualized. Figure 7 shows images of a typical LSPI occurrence. Figure 7(a) shows the cylinder pressure. Normal combustion occurs in the first cycle and then pre-ignition occurs suddenly in the second cycle. The cylinder pressure in the third cycle is close to normal combustion and pre-ignition occurs again in the fourth cycle.

The image in Fig. 7(b) was taken immediately after ignition of the mixture by the spark plug in the cycle before the start of pre-ignition. There are no floating objects in the combustion chamber that resemble an ignition source and combustion proceeds normally by spark ignition. Figure 7(c) shows the compression stroke of the cycle in which the first pre-ignition occurred. Several particles that cannot be clearly identified were observed floating in the combustion chamber from the first half of the compression stroke. Subsequently, before the spark ignition timing, pre-ignition was generated from a glowing particle appearing at the far right of the observation area (Fig.

7(d)). Immediately after this pre-ignition, large numbers of floating particles were observed in the combustion chamber, many of which were solid particles that rebounded from the piston surface. Then, as shown in Fig. 7(e), the presence of many particles was observed in the residual gas even at the start of the intake stroke of the next cycle.

Figure 7(f) shows the appearance of the combustion chamber close to the ignition timing in the third cycle. Although the cylinder pressure is close to normal combustion in this cycle, the visualization images confirm the occurrence of mild pre-ignition. However, since the ignition timing is immediately before spark ignition, the cylinder pressure changes only slightly. Therefore, these images show the well-known characteristic of LSPI, in which pre-ignition occurs every other cycle.

In other words, these images show that the cylinder pressure is close to normal combustion in the cycle immediately after a large pre-ignition event because the ignition timing of the mixture around the ignition source is delayed. This ignition timing delay is probably caused by a decrease in the temperature of the residual gas in the following cycle. The cause of the lower residual gas temperature is a substantial reduction in exhaust loss that lowers the exhaust temperature. The reduction in exhaust loss is due to higher combustion efficiency (resulting from the advanced ignition timing) and higher cooling loss (resulting from the strong knocking phenomenon), which are caused by the strong pre-ignition in the previous cycle.

Strong pre-ignition occurs again in the fourth cycle. The ignition source for this pre-ignition is a glowing particle that traversed from right to left in the observation area. This particle ignited the mixture around the position shown in Fig. 7(g).

These results can be summarized as follows.

- Particulate substances were observed prior to the start of combustion in the pre-ignition cycle. One of these particles probably reached a glowing state in the latter part of the compression stroke, thereby igniting the surrounding mixture.
- An extremely large amount of particulate substances were observed immediately after the pre-ignition. These particles probably caused the sequence of LSPIs to continue.
- These particles were observed to contact and rebound from the piston top surface, which suggests that the particles are solid. Deposit flakes are one likely candidate for the composition of these particles.
- Immediately after this strong pre-ignition, the cylinder pressure returned to close to normal combustion due to a delay in the timing of mixture ignition from the ignition source.
- The obtained images could not identify whether droplets were being scattered from the cylinder liner walls or from around the piston crevice.

ARTIFICIAL PRE-IGNITION TEST

The visualization images above suggest deposits as a likely pre-ignition source. Since Ando et al. also described the generation of pre-ignition by deposits, this research investigated the detailed characteristics of deposit ignition by injecting deposits and other substances into a combustion chamber using the method shown in Fig. 6. This study focused on identifying the required conditions for a substance to act as an ignition source, and the required conditions for pre-igniting the mixture around this substance.

Required Conditions for Substance to Act as Ignition Source

Figure 8 shows the occurrence of pre-ignition and the timing of mixture ignition when various particulate substances were injected into the combustion chamber. The injected substances were solid particles of varying diameters, including deposits obtained from the combustion chamber, combustible, and non-combustible substances. Approximately 0.1 g of each substance was injected two times. The data to the right of the graph shows the ignition timing of naturally occurring LSPI. This timing is generally distributed from 0 to 20°CA before top dead center (TDC). The ignition timing when particles were injected into the combustion chamber is shown to the left of this data. Although the number of samples is not particularly high, the timing of ignition caused by deposits is close to the ignition timing distribution of naturally occurring LSPI.

The combustible and non-combustible substances are shown to the left and right of the dotted line in the center of the graph, respectively. The occurrence of pre-ignition is clearly divided in accordance with the combustibility of the substance. However, pre-ignition also did not occur with extremely small-diameter combustible particles. In other words, the capacity to become involved in combustion and generate heat is not sufficient by itself for a particle to cause pre-ignition. The particle must be combustible and have a minimum size to form an ignition source.