

Analysis of Interaction between Autoignition and Strong Pressure Wave Formation during Knock in a Supercharged SI Engine Based on High Speed Photography of the End Gas

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ABSTRACT

Engine knock is the one of the main issues to be addressed in developing high-efficiency spark-ignition (SI) engines. In order to improve the thermal efficiency of SI engines, it is necessary to develop effective means of suppressing knock. For that purpose, it is necessary to clarify the mechanism generating pressure waves in the end-gas region. This study examined the mechanism producing pressure waves in the end-gas autoignition process during SI engine knock by using an optically accessible engine. Occurrence of local autoignition and its development process to the generation of pressures waves were analyzed under several levels of knock intensity. The results made the following points clear. It was observed that end-gas autoignition seemingly progressed in a manner resembling propagation due to the temperature distribution that naturally formed in the combustion chamber. Stronger knock tended to occur as the apparent propagation speed of autoignition increased. It is particularly notable that a condition was observed in which the apparent propagation speed of autoignition through the end gas clearly exceeded the speed of sound. Exceptionally strong knock occurred at that time. The measured results for the actual development of autoignition made it clear that extremely strong knock, such as what occurs under high-speed, high-load operation and also that induced by low-speed pre-ignition (LSPI) in a supercharged downsized engine under low-speed, high-load operation (Super-Knock), is presumably caused by such phenomena. In other word, extremely strong knock is caused by detonation phenomena produced in autoignition process.

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INTRODUCTION

Basic methods for improving the thermal efficiency of spark-ignition (SI) engines include raising the compression ratio, advancing the ignition timing optimally (i.e., minimum advance for best torque (MBT) timing), and optimal supercharged lean combustion. However, the occurrence of abnormal combustion precludes the application of these approaches. A typical example of abnormal combustion is engine knock [1], [2], [3], [4], [5], [6], such as low-speed knock that generally occurs during low-speed, high-load operation. Knock is caused by autoignition that occurs after a certain delay following spark ignition. For that reason, low-speed knock subsides when the flame propagation speed is increased by raising the engine speed.

On the other hand, it is also known that high-speed knock occurs in an even higher engine speed range. Measures for avoiding high-speed knock include lowering the effective compression ratio, retarding the ignition timing, and enriching the air-fuel mixture. However, because all of these measures cause thermal efficiency to decline, they do not lead to higher engine efficiency. Moreover, enriching the air-fuel mixture is not desirable from the standpoint of obtaining cleaner

exhaust emissions because it promotes the formation of large quantities of carbon monoxide (CO) and hydrocarbons (HCs). In order to improve this situation, it is necessary to clarify the characteristics of strong knock that occurs at high loads and to find a new approach that will effectively prevent it while at the same time increasing thermal efficiency. To accomplish that, it is necessary to make clear the mechanism causing strong knock in SI engines.

Therefore, the mechanism producing strong pressure waves and knock was investigated in this study by using a supercharged, optically accessible test engine to generate a wide range of knock intensities from weak to strong knock. Analyses were made of end-gas autoignition and its development process during engine knock operation at different levels of knock intensity.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The specifications of the test engine and the test conditions are shown in [Table 1](#). The configuration of the optically accessible engine is shown schematically in [Figure 1](#).

Table 1. Specifications of test engine

Four-stroke Single Cylinder Supercharged Optically Accessible Engine	
Bore × Stroke	85 × 70 mm
Displacement	397 cm ³
Compression Ratio	8 : 1
Valve Arrangement	Side Valves
Test Conditions	
Engine Speed, N	4000 rpm
Intake Pressure, P _{in} (abs)	130 kPa
Ignition Timing, I.T.	-50 deg. ATDC
Fuel	PRF 82.6

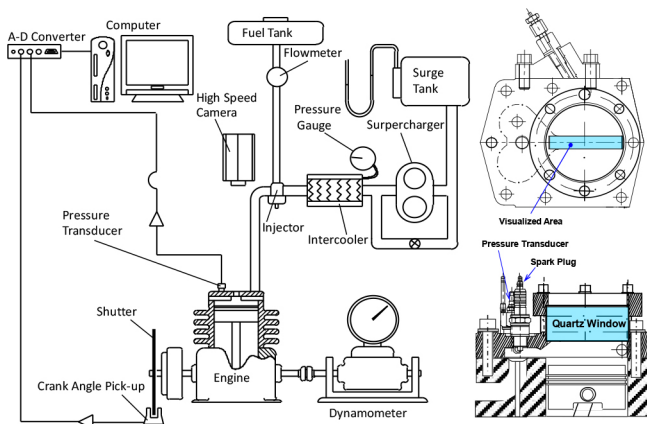


Fig. 1. Configuration of experimental setup

Experiments were conducted with an air-cooled single-cylinder test engine fitted with a supercharger driven by an external power source. As shown in Figure 1, a rectangular combustion chamber was formed in the cylinder head of the side-valve engine and was provided with quartz windows for optical access. The combustion flame formed by the spark plug on the left side of the diagram propagated rightward through the rectangular combustion chamber. Autoignition occurred in the end-gas region at the right end of the combustion chamber.

A previous report [7] presented the knock intensities measured at different engine speeds. In the present study, attention was focused on an engine speed of 4000 rpm, the condition where the strongest knock intensities were observed in the previous study. Detailed analyses were made of the development process and other aspects of end-gas autoignition. A primary reference fuel (PRF) with an octane number of 82.6 was used as the test fuel in this study. This octane number corresponds to a motor octane number (MON) in regular gasoline (JIS#2) using in this research project.

RESULTS AND DISCUSSION

Measured in-cylinder pressure histories under weak to strong knocking

A transition from normal combustion to a state of strong knock was induced in the experiments by varying the engine temperature while keeping the equivalence ratio (ϕ), engine speed (N), intake air pressure (P_{in}) and ignition timing (I.T.) constant at $\phi = 0.9$, $N = 4000$ rpm, P_{in} (abs) = 130 kPa and I.T. = -50 deg. ATDC, respectively. Because the test engine was air-cooled, the spark plug washer temperature T_{sp} was used as the engine temperature.

Figure 2 presents the cylinder pressure waveforms measured for different T_{sp} and the pressure oscillation components obtained by filtering the cylinder pressure waveforms with a 4-kHz high-pass filter. It is seen that T_{sp} rose from waveform #1 to waveform #9. The overall results show a transition to a state of strong knock as T_{sp} increased.

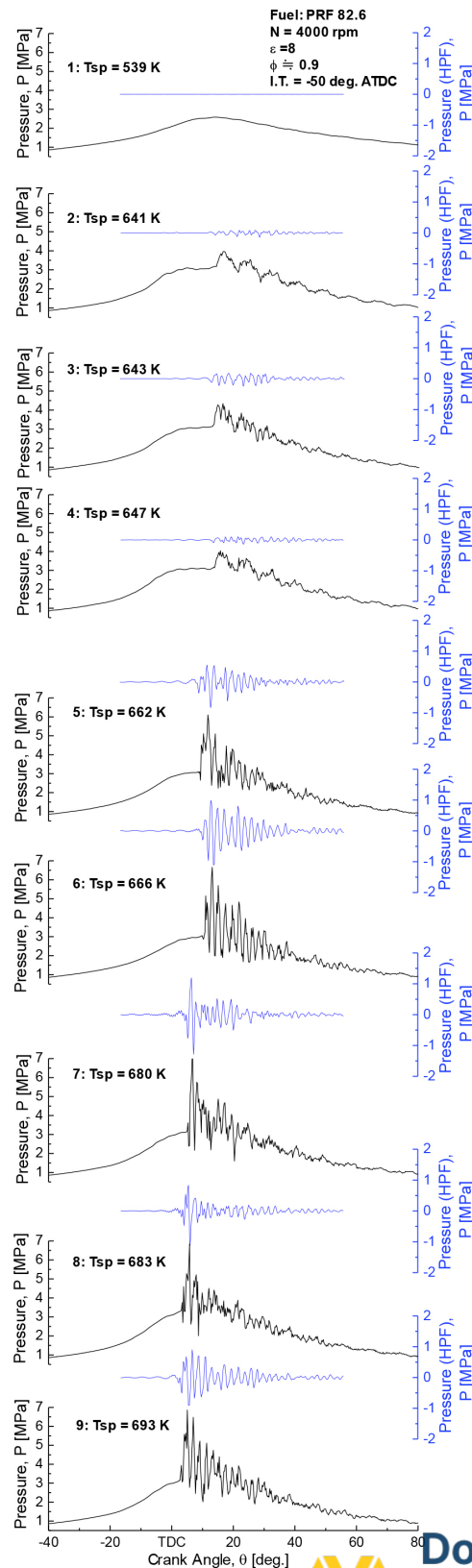


Fig. 2. Measured pressure waveforms under different engine temperature

Figure 3 shows the knock intensity P_{KI} as a function of the autoignition delay time ($\tau_{IT-\theta_{AI}}$). Autoignition delay time here refers to the time lag required from the ignition timing I.T. to the occurrence of autoignition θ_{AI} . This corresponds to the interval in which ignition and flame propagation take place. Knock intensity P_{KI} is defined as the maximum amplitude of the pressure oscillation components. It is observed that the autoignition delay time became shorter as T_{sp} rose, which was accompanied by an increase in knock intensity that led to a state of strong knock.

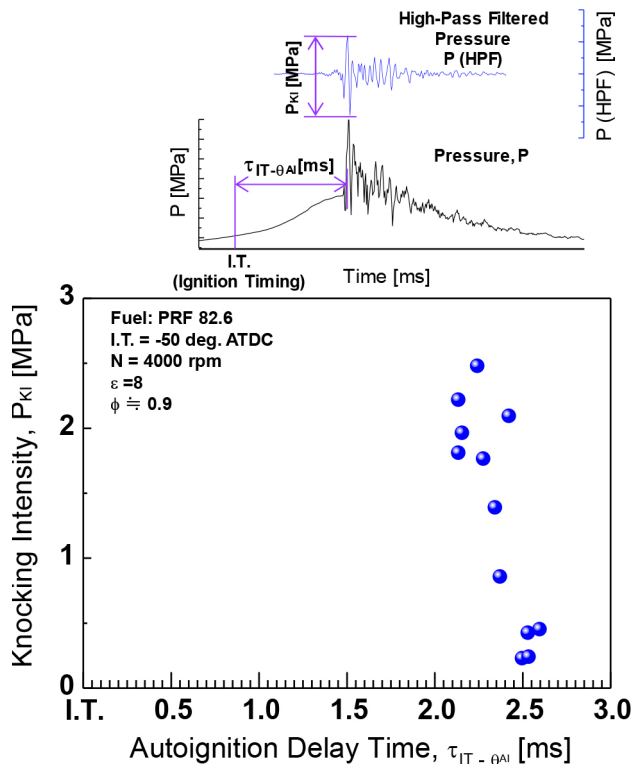


Fig. 3. Influence of autoignition delay time on knock intensity

The aim of this study was to make clear the behavior surrounding the occurrence of autoignition in the process that led to a state of strong knock. Accordingly, detailed analyses were made of the high-speed photographs taken of end-gas autoignition that occurred under the conditions present at that time.

Investigation of Development Process of Pressure Waves and Knock Based on Analysis of End-Gas Autoignition Propagation Speed

The method used in this study to analyze the development process of end-gas autoignition will be explained first. Figure 4 presents typical combustion images obtained experimentally and an outline of the method used for analyzing the autoignition propagation speed.

Images were obtained at a frame rate of 480,000 frames/s (fps) and photographing was initiated at a sufficiently early timing. That was done to ensure that combustion would be photographed with sufficient time resolution even if end-gas autoignition progressed at a supersonic speed. Flame propagation initiated at the spark plug positioned on the left side of the figure progressed rightward, and the right side of the combustion chamber was the end-gas region.

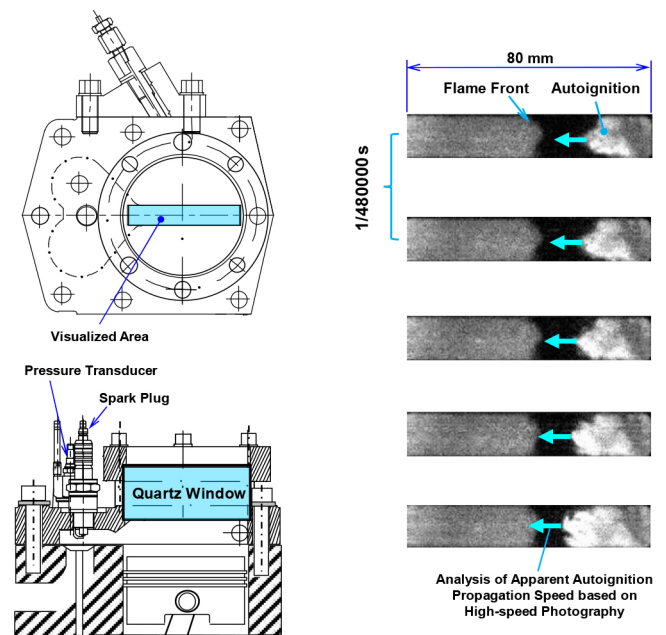


Fig. 4. Typical visualized images of knocking combustion and method of analyzing autoignition propagation speed

Because there are always temperature, residual gas and other distributions in an actual combustion chamber, the end gas does not all autoignite simultaneously, but rather autoignition occurs locally with a time difference between locations. If there is a distribution conducive to autoignition in a certain direction, autoignition initiated at the most favorable location spreads successively into the surrounding area such that it appears to be propagating. In the combustion images obtained in the test engine, many cases were observed like that in Figure 4 where autoignition that began near the wall on the right end propagated successively leftward (on the propagating flame side). Therefore, the apparent propagation speed of autoignition was analyzed by regarding this propagation as being one-dimensional. Using this approach, the autoignition propagation speed was analyzed under the conditions indicated in Figures 2 and 3.

However, the experimental data included cases in which autoignition developed and spread from other locations besides the right end of the combustion chamber. Figure 5 presents an example of visualized images showing the occurrence of autoignition at multiple locations and its subsequent propagation. In this case, it was not possible to analyze the apparent autoignition propagation speed as being that of one-dimensional propagation. Therefore, these measured results were excluded from the analysis of the autoignition propagation speed.

Figures 6, 7, 8 show examples of the analysis results for the autoignition propagation speed in relation to the measured results denoted as waveform #4, waveform #6 and waveform #9 in Figure 2. The lateral length of the visualized region was 80 mm. Combustion was photographed at a frame rate of 480,000 fps (2.1 μ s/frame). Therefore, the images were arranged according to the relationship between time t and distance x , making it possible to analyze the apparent autoignition propagation speed based on the slope of the trajectory of the autoignition propagation front.