

The Effects of Ignition Environment and Discharge Waveform Characteristics on Spark Channel Formation and Relationship between the Discharge Parameters and the EGR Combustion Limit

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ABSTRACT

In order to realize the high compression ratio and high dilution combustion toward improvement in thermal efficiency, the improvement in stability of ignition and initial phase of combustion under the high gas flow field is the major challenge. In terms of the shift on the higher power side of the operating point by downsizing and improvement of real world fuel consumption, the improvement of ignitability is increasingly expected in the wide operating range also including high load and high engine speed region. In this study, the effects of the gas pressure, gas flow velocity near the spark gap at ignition timing, and discharge current characteristics on spark channel formation were analyzed, focusing on restrike event and spark channel stretching in the spark channel formation process. And the relationship between the average discharge current until 1 ms and the EGR combustion limit was considered.

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INTRODUCTION

Countries around the world are further tightening their fuel economy regulations from the standpoints of ensuring energy security and addressing global warming. In this context, one of the greatest issues of concern is to improve the thermal efficiency of internal combustion engines that will continue to be the principal automotive powertrain in the foreseeable future.

Major trends toward improving thermal efficiency include raising the compression ratio and adopting highly diluted combustion achieved by applying a heavy exhaust gas recirculation (EGR) rate and a lean mixture. Implementing these measures has increased the importance of the ignition system that triggers the start of combustion and influences fluctuations in the early combustion phase. Improvement of the ignition system is strongly desired over a wider range of operating conditions, including the high-speed, high-load region. This is related to the shift of the engine operating point toward the higher power side as a result of the recent trend toward engine downsizing and the improvement of real-world fuel economy. Against this backdrop, there have been many reports of studies concerning methods of predicting ignition in spark-discharge ignition systems [1,2] as well as research about various types of next-generation ignition systems [3,4,5,6,7,8], which suggests a heightened interest in ignition technologies.

Combustion fluctuations under a highly diluted condition can be suppressed by increasing the turbulent flame speed to shorten the combustion period. A well-known way of accomplishing that is to create a highly turbulent flow field in the cylinder using a control device for strengthening the gas flow, among other methods. The required gas flow level increases with a higher degree of mixture dilution, which, together with the advance of the ignition timing, also tends to increase the gas flow velocity near the spark gap at the time of ignition.

In a spark discharge ignition system, increasing the gas flow velocity in the spark gap has the potential to inhibit early combustion fluctuations by shortening the initial combustion period. That is because the increased gas flow stretches the spark channel, which expands the spatial spark discharge volume, resulting in the formation of a relatively large initial flame kernel. On the other hand, a higher gas flow velocity can cause spark blowout and restrikes (reignition) [9] in the spark channel, with the result that the spark channel does not stretch in the direction of the gas flow. As a consequence of spark blowout in the spark channel, cycle-to-cycle spark formation may become unstable, which can also cause a problem of larger cycle-to-cycle fluctuation in the interval from initial flame formation to the early phase of combustion. Cycle-to-cycle fluctuation in the initial combustion phase has the effect of causing the subsequent main combustion period to fluctuate, thus limiting the region where diluted

combustion is viable. Suppressing misfiring and the occurrence of partial burn due to extremely late initial combustion are indispensable to improving the stability of diluted combustion.

Accordingly, it is assumed that suppressing spark blowout under a condition of a high gas flow velocity is essential for stable spark channel stretching. For that reason, it is important to have a better understanding of the spark channel formation process, including the occurrence of spark blowout and restrikes. The formation of the spark channel is presumably influenced by the gas pressure (density), gas flow velocity and discharge waveform characteristics at the time of ignition, making it necessary to understand the actual effects of these parameters in practical terms.

There are various examples of previous studies that focused on spark discharge phenomena. Pashley et al. [10] derived an experimental model of breakdown voltage and inductive discharge voltage based on spark discharge experiments conducted with a constant volume chamber. Lee et al. [11] investigated changes in the voltage and discharge duration of arc and glow discharges in relation to changes in gas pressure in a quiescent field. Kim and Anderson [12] described the changes in discharge voltage shapes and restrike frequency in relation to gas flow velocity changes under atmospheric pressure. However, there are no reports of studies that focused on restrikes and spark channel stretching under a condition of high gas pressure (density). Among examples of recent studies, Zhang et al. [13] investigated the effect on initial flame formation of differences in multiple spark discharge patterns in a high flow velocity, highly diluted environment with a high EGR rate and a lean mixture in a pressurized combustion chamber. Chen et al. [14] investigated the relationship between the EGR limit of the engine and various discharge patterns by controlling the superimposition timing of two ignition coils. However, the relationship with spark channel formation, which is an intermediate index of spark discharges, is still unclear.

In this study, the effects of the gas pressure (density), gas flow velocity and discharge waveform characteristics on spark channel formation, including spark blowout and restrikes, were analyzed by synchronizing time histories of the discharge voltage/current waveforms and the spark channel behavior during the discharge duration. Ignition coils with different discharge waveform characteristics and a constant volume chamber that allowed the gas pressure (density) and gas flow velocity to be controlled at the time of spark discharge were used to obtain experimental data for analysis. In addition, a single-cylinder engine was used to investigate the relationship between the parameters of the discharge waveform characteristics and the EGR combustion limit.

EXPERIMENTAL EQUIPMENT

Constant Volume Chamber Experiments

The constant volume chamber used in this study is shown in Figure 1. Observation windows were provided on three sides of the chamber and a fan for simulating the in-cylinder gas flow was installed on the chamber wall without a window. The fan was capable of generating a maximum flow field velocity of 7.9 m/sec in the spark plug gap. Gas

flow guides were installed in the chamber to suppress turbulent flow. A laser Doppler velocimetry (LDV) was used to measure the gas flow velocity in the spark gap. The conditions for the spark discharge in air in this study were an ambient gas pressure range from atmospheric pressure to 1000 kPa, a constant ambient gas temperature of 25 deg. C, and a gas flow velocity range in the spark gap of 0-7.9 m/sec.

The spark plug was positioned in the center of the chamber. The outside electrode of the spark plug was oriented almost perpendicular to the gas flow direction so as not to impede the gas flow in the spark plug gap. A 2-prong spark plug with a mass production specification of a 1.1-mm spark gap was used.

The discharge voltage and current waveforms during spark discharge were measured with a high-speed oscilloscope (500 kHz) and recorded in a PC via a LAN cable [15]. Measurements were obtained with a high-voltage probe (Tektronix P6015A) from the middle of the high-tension cable and with an AC current probe (Pearson 110A) attached from directly above the plug. Simultaneously with the discharge waveform measurement, a high-speed camera (Photron FASTCAM SA 1.1) was used to take direct color photographs of the spark channel formation process at a frame speed of 25000 fps.

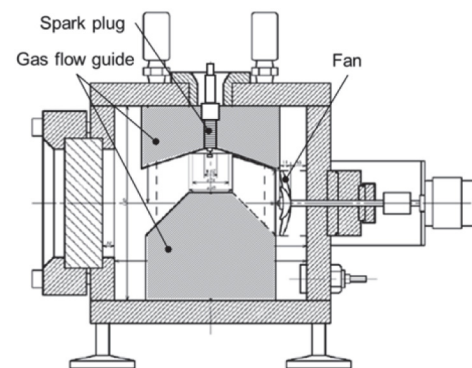


Figure 1. Constant volume chamber

Ignition Coils

Three types of ignition coils with different turns ratios were used in the experiments: a high-current type, a long-discharge type and an intermediate type between the other two. The intermediate type, high-current type and the long-discharge type will be referred to here as coils A, B and C, respectively [15]. Figure 2 shows the discharge current waveforms of the three coils during discharge in air at approximately 50 mJ. The discharge energy of coils A, B and C was evaluated in a range of approximately 50-100 mJ by varying the coil charging time.

In addition, an ignition system capable of sustaining a high current value was also used for the purpose of evaluating the current characteristics over a wide range. With this system, DC voltage from a DC-DC converter was introduced directly on the secondary side of the ignition coil [16]. This system will be referred to here as coil D. The DC voltage introduced on the secondary side of coil D was controlled so as to vary the sustained current value and duration

following spark discharge. Figure 3 shows the discharge current waveforms of coil D during discharge in air over the entire range of evaluation conditions from approximately 65 mJ to 230 mJ.

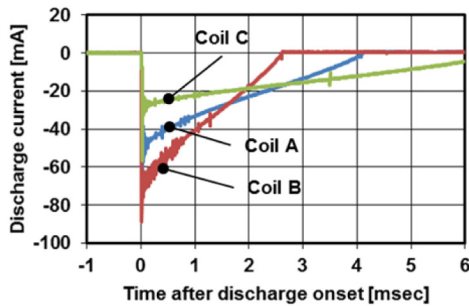


Figure 2. Discharge current waveforms of coil type A, B, and C during discharge in air

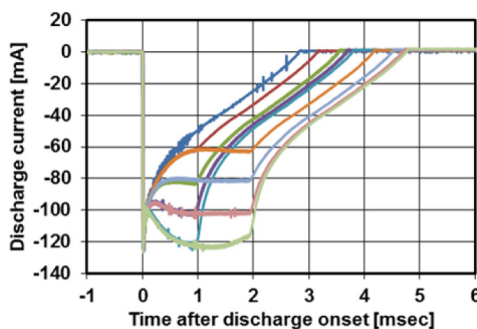


Figure 3. Discharge current waveforms of coil type D during discharge in air

Single-Cylinder Engine Experiments

The specifications of the test engine used in this study are given in Table 1. A 4-valve single-cylinder engine with a pentroof combustion chamber was used. The fuel injector was installed in the intake port and the spark plug was positioned in the center at the top of the combustion chamber. A tumble control plate with an aperture ratio of 30% was installed at the intake port inlet to strengthen tumble flow. The in-cylinder pressure was measured with a sensor inside the cylinder and the pressure data were sent to a combustion analysis terminal via a charge amplifier and a data recorder. The heat release rate was calculated from the recorded in-cylinder pressure data. The discharge voltage and current measured in each cycle were input into the combustion analysis terminal, and the discharge data in each cycle were recorded simultaneously with the combustion data.

Table 1. Test engine specifications

Engine Type	4-Stroke, Single cylinder
Displacement	499 cm ³
Bore x Stroke	84.0 x 90.1 mm
Compression Ratio	13:1
Intake Valve Open - Close	10 deg. BTDC – 50 deg. ABDC
Exhaust Valve Open - Close	40 deg. BBDC – 0 deg. ATDC
Fuel System	Port-Injection
Fuel	Gasoline (100 RON)

EXPERIMENTAL RESULTS AND DISCUSSION

Spark Channel Formation Process

This subsection presents the results of observations made of the spark channel formation process, including spark blowout and restrikes, using the constant volume chamber and typical experimental conditions. The conditions used here were an ambient gas pressure of 500 kPa, ambient gas temperature of 25 deg. C, gas flow velocity in the spark gap of 7.9 m/sec, coil A (intermediate type) and discharge energy of 50 mJ.

Figure 4 shows time histories of the discharge voltage and current waveforms and spark channel formation during the discharge. The discharge voltage waveform displays a saw-shaped profile that includes spark blowout and restrikes. It is observed that breakdown occurs following the onset of discharge and a spark channel forms in the spark gap (Figure 4-[A]). The voltage returns to nearly zero accompanying the decline in discharge resistance, but the discharge resistance increases as the spark channel stretches in the gas flow direction and the discharge voltage rises at the specified slope (Figure 4-[B]). Subsequently, the spark channel stretches further and when the discharge voltage reaches a certain given value (referred to here as the restrike voltage), the stretched spark channel is extinguished; simultaneously, a short spark channel newly forms again near the spark gap at a position slightly removed in the gas flow direction (Figure 4-[C]; first restrike). The spark channel newly formed by the restrike stretches in the gas flow direction, and the discharge voltage similarly rises (Figure 4-[D]). It is seen that these phenomena are then repeated. Images of the spark channel at the time of the subsequent 2nd to 4th restrike are shown in Figure 4-[E], [F] and [G]. A close examination of the time to the occurrence of a restrike ($t_{r1}-t_{r4}$) reveals that the interval gradually shortens in the latter half of the discharge when the discharge current becomes smaller. Accordingly, the length of the spark channel is the longest just before the first restrike occurs.

Effect of Gas Pressure and Flow Velocity on Spark Channel Stretching

The preceding subsection explained the spark channel stretching process, including the occurrence of spark blowout and restrikes in the spark channel. This subsection presents the results of an analysis of the effect of the gas pressure (constant gas temperature of 25 deg. C) and gas flow velocity on spark channel stretching based on the data obtained with ignition coil A (intermediate type).

Figure 5 shows images of the largest spark channels typically observed just before the first restrike in relation to the gas pressure and the gas flow velocity. Figure 6 shows a map of the average spark channel length ($n = 10$) just before the first restrike event. The results in these two figures indicate that the spark channel length tended to increase under relatively high gas pressure and gas flow velocity.