38 A Study on Optimum Condition of Multiple Spark Discharge

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In order to clarify mechanism of the optimum spark interval of multiple spark discharge, the effects of spark kernel interval on flame kernel development and burning time were investigated using two successive sparks with spark interval of 200 μs to 600 μs. Numerical simulation was done to study effects of the second spark discharge on flame kernel formation. The experimental results show that the optimum spark interval giving the shortest burning time is 300 μs and that increase in spark energy causes shorter burning time. The calculated flame kernel well explains interaction between the initial flame kernel by the first spark and that by the second spark.

***Kewords*: Ignition, Spark Ignition Engine, CDI, Multiple Spark Discharge**

1. INTRODUCTION

High ignition ability of spark ignition system of internal combustion engines contributes to improvement of exhaust emission and reduced fuel consumption using lean burn technology. Increasing ignition energy as a simple solution for higher ignition ability results in forwarding erosion of spark plugs and need of a more powerful battery. Multi spark ignition system [1-4] which provides several spark discharge of relatively short duration, is one of suitable ways for progress of engine performance. Usually the multi spark ignition system is based on capacitor discharge ignition (CDI). CDI has advantages of higher RPM capability because of its very short build-up time of primary voltage and less carbon fouling of spark electrodes, while its disadvantage is less ignition ability due to short spark duration, as compared to transistor controlled ignition system. However, it is able to remove this weakness by multiplying spark times.

In terms with the leading study on multiple spark discharge, the effect of discharge frequency on ignition ability has been investigated using capacitance sparks [5] and it is found that the ignition ability reaches a maximum value at a spark interval of 10 μs to 50 μs, which corresponds to the discharge frequency of 50 kHz to 10 kHz. As for tests in spark ignition engines, it is reported that the optimum spark interval for maximum engine torque is 100 μs [1]. This indicates that well-desired multi spark ignition system contributes to increase in engine power as well as improvement of ignition ability.

In the present work a fundamental study was conducted to clarify mechanism of the optimum spark interval of multiple spark discharge realizing the shortest burning time. Two successive spark discharges using CDI were given to a quiescent mixture introduced into a combustion chamber. Numerical simulation was also done to study effects of multiple spark discharge on flame kernel formation.

2. EXPERIMENTAL APPARATUS

2.1. Combustion Chamber

Figure 1 shows a sectional view of the combustion chamber, whose internal diameter is 30 mm and depth is 30 mm. A couple of quartz windows were fitted to the chamber for visualization of flame kernel development. A pair of spark electrodes, which were made of stainless wires of 0.6 mm in diameter, was placed at the center of the chamber. The spark gap width was 1.0 mm throughout the present experiment. A conventional pressure transducer was fixed to the chamber wall for measurement of burning time, which was defined as time from onset of spark discharge to maximum in the pressure record.

Experimental apparatus is shown in Fig.2. A conventional high voltage probe and a current probe were connected with a wire between one of the spark electrodes and the ignition unit to estimate energy given in the spark gap. As a test gas, a propane-air mixture with an equivalence ratio of 0.85 was fully mixed in a tank and then introduced into the combustion chamber. The initial pressure and temperature were 101 kPa

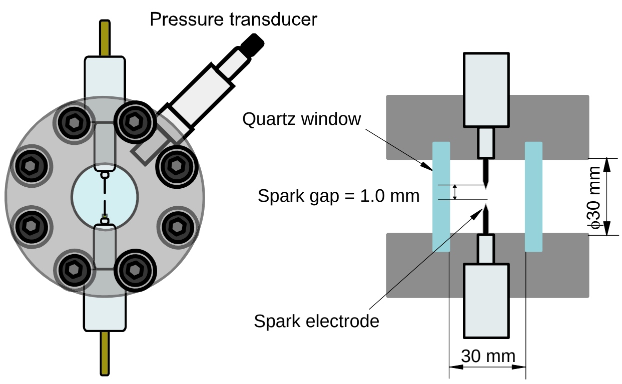

Fig. 1 Schematic of combustion chamber.

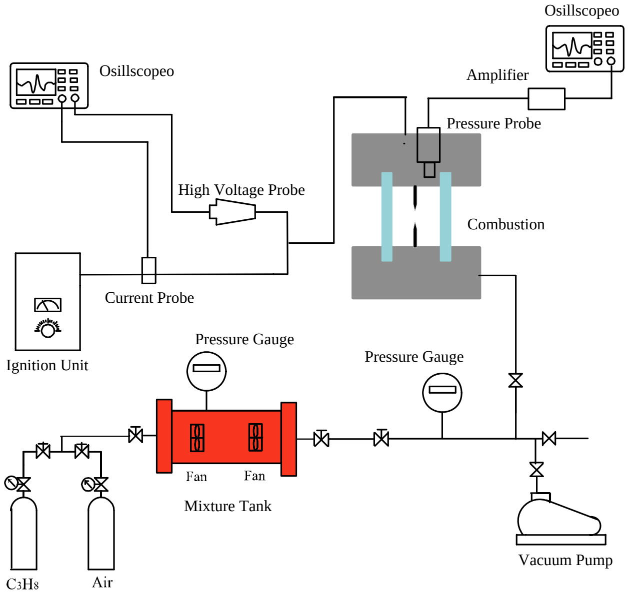

Fig. 2 Experimental set-up.

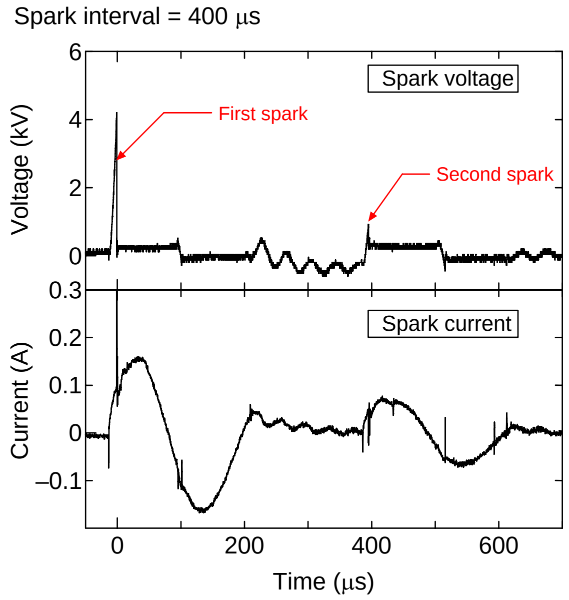

Fig. 3 Typical time history of spark voltage and spark current of two successive sparks. Spark interval: 400 us.

and room temperature, respectively. Under each condition, tests were repeated over 30 times. It was confirmed that ignition ability of 100 % was achieved under the present experimental conditions.

2.2. Ignition System

The ignition system was designed to generate multiple spark discharge with a desired spark interval. Since conventional multi spark ignition system based on CDI has one capacitor bank and one thyristor, it is difficult to change energy of each spark discharge individually. The present ignition system consists of three same CDI units combined with one ignition coil so that energy and discharge timing of successive sparks can be controlled independently by changing capacitance and giving a gate signal to individual thyristor. In the present work, two CDI units of the ignition system were activated to study effects of spark intervals between the first and the second spark discharge on flame kernel development.

Typical voltage and current traces of two successive sparks are shown in Fig. 3. After breakdown process, a capacitance component of duration less than 1 μs was followed by the oscillatory waveform, which is due to *LC* oscillator composed of the capacitor and the ignition coil. At 200 μs after breakdown the thyristor turns off, indicating end of spark discharge. At this moment the oscillation is not yet fully attenuated and some charges are still left in the capacitor so that all energy initially stored in the capacitor is not fully released in the spark gap. As for the second spark, breakdown voltage was much less than at the first spark, which is due to existence of weakly ionized gas in the spark gap. From duration of the first spark discharge, the spark interval was varied from 200 μs to 600 μs in the present work.

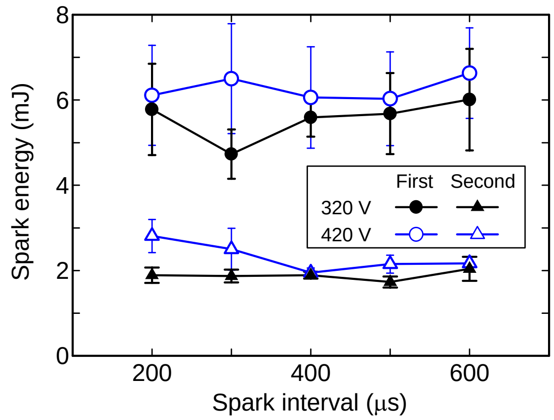

Fig. 4 Spark energies of the first and second spark for various spark intervals.

Energy of the first and the second spark was estimated by integration of voltage multiplied by current, as shown in Fig. 4. The spark energy estimated in this manner is less than 20 % of energy initially stored in the capacitor. This is mainly due to loss of connecting wires and residual charges in the capacitor. Although spark energies slightly vary with the spark interval, it is confirmed that almost the same spark energy can be obtained under the same charging voltage.

3. MODEL DESCRIPTION

Numerical simulation has been conducted to clarify effects of multiple spark discharge on flame kernel formation. The model used in the present work was essentially the same as that treating ignition process by short duration sparks [6, 7]. The partial differential equations of mass and momentum conservation based on a two-dimension cylindrical coordinate were implicitly integrated in an iterative manner using a part of

(a) Time = 50 μs (b) Time = 500 μs (c) Time = 1000 μs (d) Time = 2000 μs

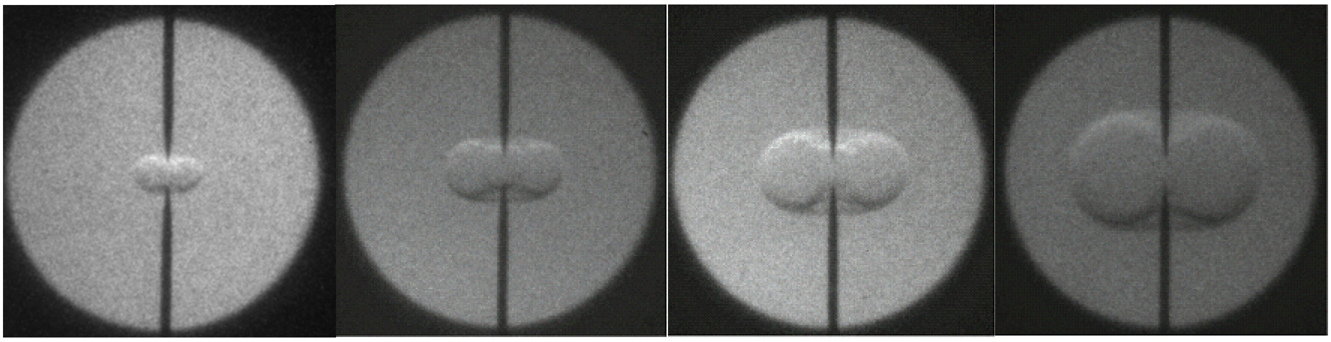

Fig. 5 Schlieren photographs of flame kernel development. Spark interval: 300 μs; charging voltage: 420 V.

Time = 100 μs

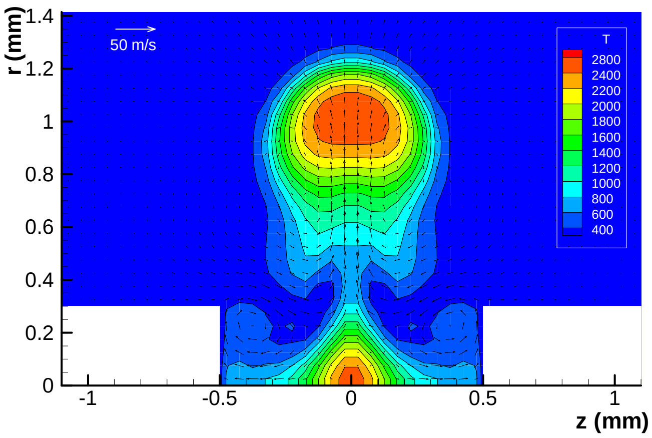

Fig. 6 Calculated temperature and velocity distributions. Spark interval: 300 μs. Two white rectangulars denote spark electrodes.

RICE code [8]. Then equations of energy and species conservation were solved explicitly. Convective terms were treated with QUICK scheme [9] which gives third-order accuracy in space.

Chemical species were assumed to be propane, oxygen, nitrogen, and combustion product and a one-step overall reaction was used as chemical reaction [6,7]. Temperature dependence of viscosity and thermal conductivity was also considered.

To simulate spark discharge, internal energy was given in the spark gap during spark duration. Energy of the first and the second spark discharge was 0.44 mJ and 0.19 mJ respectively. Based on numerical stability, cell size and time step were taken to be 0.05 mm and 0.02 μs, respectively.

4. RESULTS AND DISCUSSON

4.1. Flame Kennel Formation

Figure 5 shows schlieren photographs of flame kernel generated by two successive spark with spark interval of 300 us. In Fig. 5 (a) a toroidal flame kernel is formed which is characteristic of short duration sparks [6, 7]. In Fig. 5 (b) hot region generated by the second spark discharge is observed inside the torus. Afterwards the hot gas region was merged with the initial flame kernel and any distinct hot region separated from the toroidal kernel cannot be seen in the spark gap as shown in Fig. 5 (d).

This flame kernel formation can be explained with the calculated results. Figure 6 shows temperature and velocity distributions at 100 μs. At this stage, the second spark discharge does not yet occur and the toroidal flame kernel is caused by the first spark discharge. Formation process of the toroidal flame kernel has been already clarified by numerical simulation [6, 7]. Just after energy release of the capacitance component an ellipsoidal flame kernel is formed in the spark gap. A part of this kernel is then transformed into a torus by a pair of vortices that rotate in opposite senses [7]. A cold surrounding gas moving into the flame kernel causes a ring of the torus and contributes to radial development. Since flow stagnates at the center of the spark gap, the hot region left in the spark gap gradually decays due to heat transfer to the surroundings. In the present ignition system each spark is composed of a capacitance and the subsequent inductive component generated by the *LC* oscillator mentioned before. Energy of the inductive component itself, which actually contributes to successful ignition, is not enough to maintain self-sustained flame.

In Fig. 7 the interaction process between the initial toroidal kernel and the hot gas kernel generated by the spark discharge is shown for the spark interval of 300 μs. In Fig. 7 (a), there can be seen the groove inside the ring of torus and hot region decayed in the spark gap. In Fig. 7 (b), namely 100 μs after the second spark discharge, hot gas kernel is formed in the spark gap again by energy input of the second spark beginning at 300 μs. This kernel grows radially outwards so that it intrudes into the groove of the torus. In Fig. 7(c) the hot gas kernel is merged with the toroidal flame kernel and it must be noted that a cold gas pocket is captured at the center of the ring of the torus. Although the cold gas pocket decreases temperature of

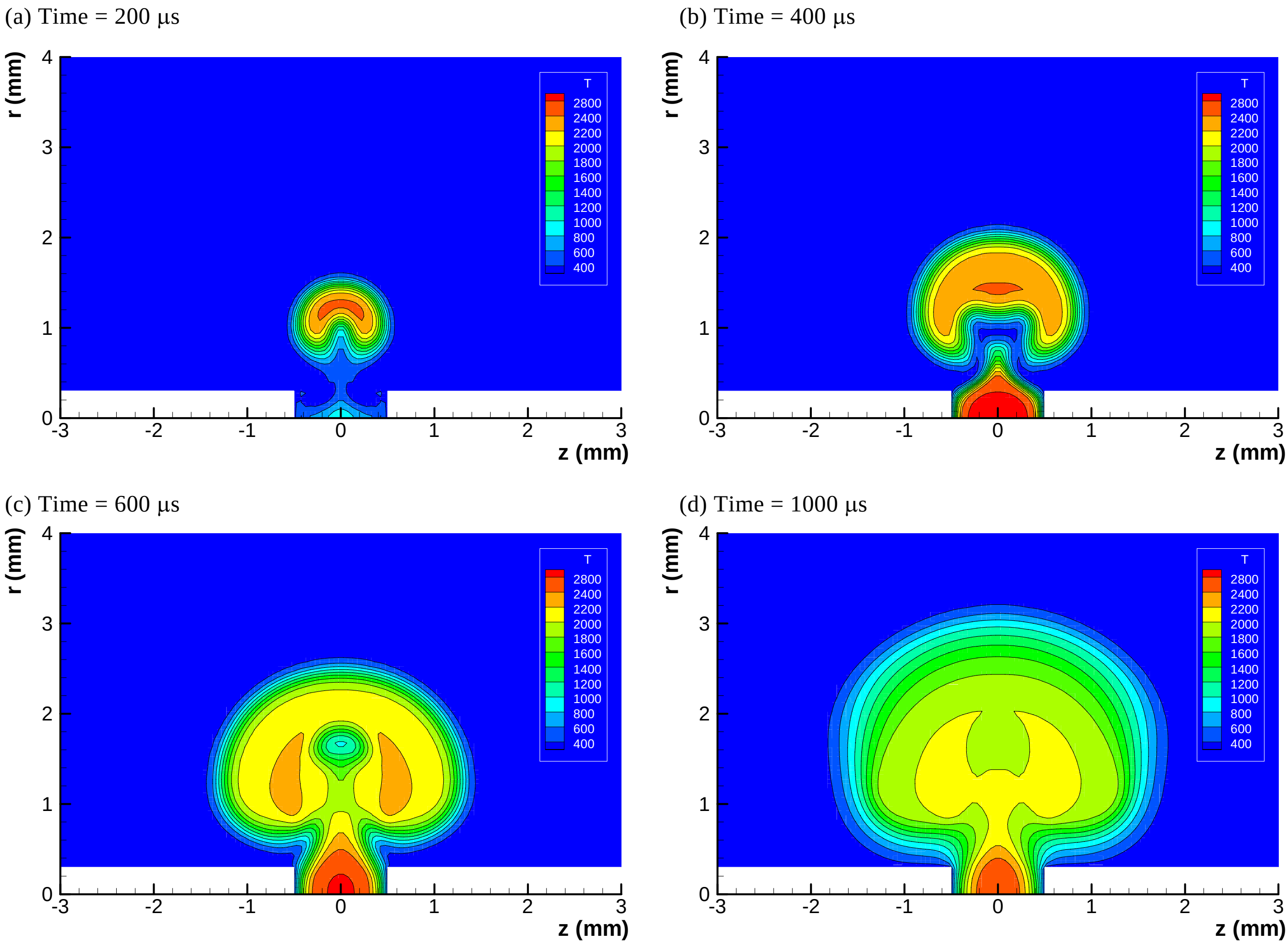

Fig. 7 Calculated flame kernel development. Spark interval: 300 µs.

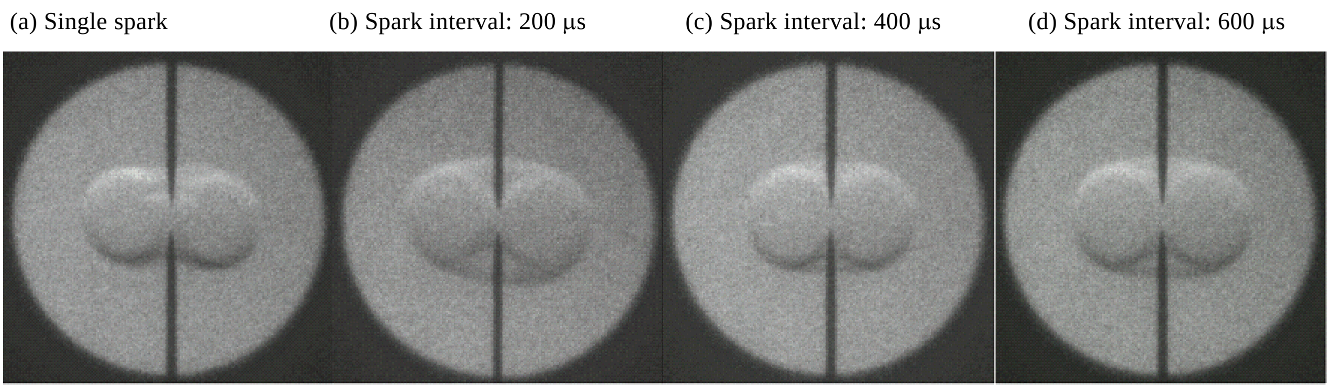

Fig. 8 Schlieren photographs of flame kernel development at 2000 µs after breakdown. Charging voltage: 420 V.

the flame kernel from inside to some extent, it continues to develop afterwards, as shown in Fig. 7 (d).

This scenario is also applicable to cases with the other spark intervals. Figure 8 shows schlieren photographs for various spark intervals, where the flame kernel generated by single spark is also shown for comparison. Overview of these flame kernels resemble each other, since absolute energy of the second spark is almost one-third of the first one and the kernel shape is mostly governed by the first spark discharge. However there are small differences in the shape of flame kernel. As compared to the case of single spark in Fig. 4 (a), the flame kernel expands in the direction of the spark electrode for the spark interval of 200 µs in Fig. 4 (b). Increase in the spark interval results in merging of the hot gas kernel by the second spark, which grows in the hollow space of the torus, with the well-developed initial flame kernel. This merging does not directly connected to faster flame kernel development, since the following flame propagation process is originated from the initial toroidal flame in these cases.

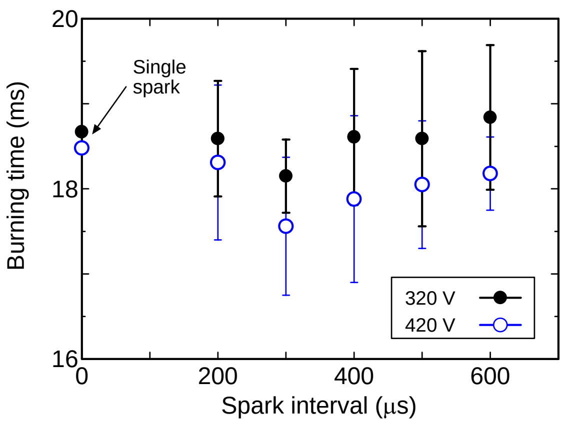

Fig. 9 Effects of spark intervals on burning time.

4.2. Effects of Spark Interval

Figure 9 shows effects of spark interval on the burning time. It is well demonstrated that the optimum spark interval, which gives the fastest combustion process, is 300 μs for the both charging voltages. This value is slightly different from 100 μs in the engine test [1] and much larger from 10 μs to 50 μs in the case of capacitance sparks [5]. This is probably because manner of contribution of the second spark to the initial flame kernel is not the same as in the present work. In the combustion chamber of the engine there exists a turbulent flow field, which promotes cooling effect of a surrounding gas, namely heat transfer from the flame kernel to the surrounding. Optimum timing of the flame kernel merging may become faster to compensate the cooling effect. As for the difference from capacitance sparks, the spark generated by the present ignition system contains an inductive component as shown in Fig. 3. As a consequence temporal distribution of spark power is much different from the case of capacitance sparks, for which all

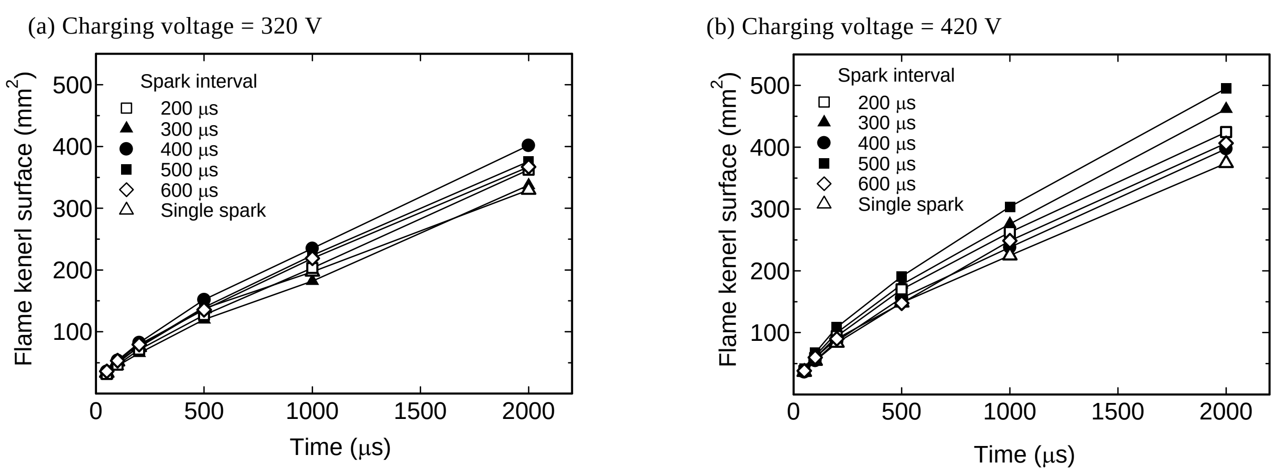

Fig. 10 Flame kernel surface estimated from schlieren photographs for various spark intervals.

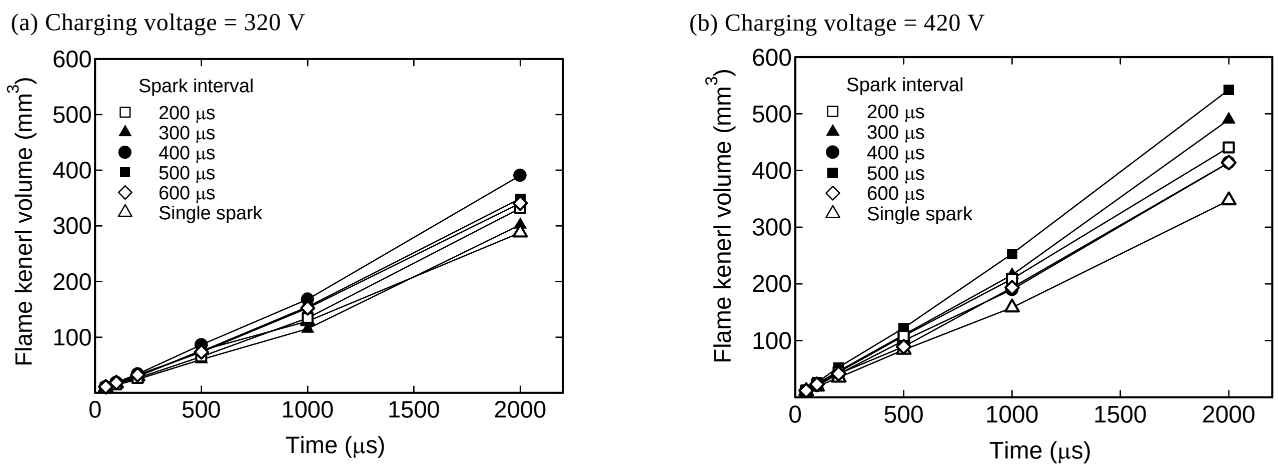

Fig. 11 Flame kernel volume estimated from schlieren photographs for various spark intervals.

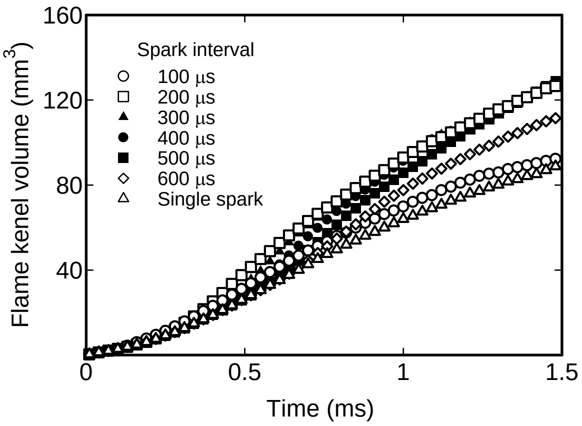

Fig. 12 Calculated flame kernel volume for various spark intervals.

spark energy is released in less than 1 μs. This means that a larger flame kernel exits at the end of spark discharge, corresponding to faster development of flame kernel. From this it is therefore reasonable that the optimum spark interval is larger in the case of CDI than in capacitance sparks.

Figure 9 also indicates that increase in charging voltage, i.e. increase in spark energy causes shorter burning time. Maly et al. reported that increase in spark energy does not manifest itself in higher kernel temperature and that instead the channel diameter increases, causing a larger activated gas volume [10]. In the case of small spark energy, even when successful ignition is obtained, longer time is needed for flame kernel development than in large spark energy. This is also the case that the engine torque increases with the spark times of multi spark ignition system in the engine test [1]. The effect of spark energy on flame kernel size can be confirmed in Fig. 10 and Fig. 11 showing surface and volume of flame kernel estimated from the schlieren photographs. For simplicity, the flame kernel was treated as cylindrically symmetric and then both surface and volume of the flame kernel were calculated using Pappus-Guldinus theorem under the assumption that the cross section of the flame kernel consists of two adjacent ellipses. From Fig. 10 and Fig. 11, apparently multiple spark discharge causes larger flame kernel as compared to single spark discharge. Difference in the flame kernel volume between the two charging voltages is consistent with the results of Fig 9.

As for effects of the spark interval, slower flame kernel development is obtained for 200 μs and 600 μs in Fig. 10 and Fig. 11. However, the optimum spark interval of 300 μs obtained from the pressure record is not well recognized, which may be resulted from accuracy of the estimated flame kernel surface and volume. The assumption that the cross section of the flame kernel consists of two adjacent ellipses has validity for single spark generating flame kernel of a toroidal form. On the other hand, it is rather difficult to capture the exact outer contour of the flame kernel using schlieren photographs taken only from one direction, since hot gas kernel by the second spark lies in the spark gap for multiple spark discharge.

The experimental result that the optimum spark interval exits is also confirmed by the numerical simulation as shown in Fig. 12, although there is difference between the experimental and calculated value of flame kernel volume, which is responsible for values of given spark energy. The calculated time history of the flame kernel volume shows that spark intervals of 200 μs to 400 μs are optimum, which agrees well with the experimental results. In addition, spark interval of 100 μs, which was not realized in the experiment, shows the smallest flame kernel among the multiple spark discharge.

4. CONCLUSIONS

In order to clarify mechanism of the optimum spark intervals of multiple spark discharge, the effects of spark kernel interval on flame kernel development and burning time were investigated using two successive sparks with spark interval of 200 μs to 600 μs. Numerical simulation was done to study effects of the second spark discharge on flame kernel formation. From the present work, the following results were obtained:

(1) The optimum spark interval giving the shortest burning time is 300 μs under the present experimental condition.
(2) Increase in spark energy gives larger flame kernel, causing shorter burning time.
(3) Calculated flame kernel well explains interaction between the flame kernel generated by the first spark and that by the second spark.
(4) Numerical simulation supports the existence of the optimum spark interval.

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