Spark Ignition Properties of Combustible Mixtures under High-Turbulence-Intensity Conditions*

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Spark ignition properties of combustible mixtures under high-turbulence-intensity conditions were studied using an ignition device which was able to vary the energy of capacitance and subsequent inductance sparks, independently. The high-intensity turbulence field was generated by mutual collision of injected mixtures at the center of a cylindrical combustion chamber. From observation of schlieren photographs of flame kernel development, it was found that the turbulence had little effect on the flame kernel shape in the incipient stage of ignition process. The experimental results showed that addition of the subsequent spark to the capacitance one improved ignition ability especially under high-turbulence-intensity conditions, and that high ignition ability appeared with an increase in the ratio of the subsequent spark energy to the total spark energy.

Key Words: Internal Combustion Engine, Turbulence, Flame, Combustion, Spark Ignition, Ignition Ability, Composite Sparks, Minimum Ignition Energy

1. Introduction

In recent SI engines, high turbulence fields are created in the combustion chamber owing to the need for quick flame propagation when employing lean burning. However, the turbulence, which plays an important role in quick burning, often causes a misfire due to a quenching effect⁽¹⁾. The ignition process is very complicated because the process is affected significantly by interactions such as those between the flame kernel blown from the initial position and spark electrodes⁽²⁾, or between the flame kernel expanded or distorted by the turbulence and unburnt mixture.

Former experimental studies on the ignition process in turbulence fields were performed by using a grid set in a gas flow⁽¹⁾, a moving porous plate⁽³⁾ and rotating fans in a closed chamber⁽⁴⁾⁻⁽⁶⁾. In these methods, however, the turbulence intensity was relatively weak, and the effects of turbulence itself on the flame kernel

development could not be identified clearly since the interactions of the flame kernel with the spark electrodes and the effects of turbulence coexisted in a mainstream field. To examine the effect of turbulence itself on a spark ignition process, in the work, a high-intensity turbulence field without mainstream was generated by mutual collision of injected mixtures. The effects of turbulence intensity on the minimum ignition energy and flame kernel growth were studied using an ignition device which was able to generate composite sparks simulating a conventional ignition system.

2. Experimental Apparatus and Procedure

The high-intensity turbulence field was created by mutual collision of injected mixtures at the center of the cylindrical combustion chamber, as shown in Fig. 1. The chamber was provided with glass windows at both ends of the cylindrical axis for optical access. The inner diameter and length were 40 mm and 30 mm, respectively. Four nozzles were set equally round the circumference, pointed toward the center. The inner diameter was 3 mm. The nozzle injection velocities were controlled by four valves set before the

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nozzles so that the mainstream velocity could be kept at zero at the center of the chamber. Stainless wire (diameter: 0.2 mm) was used as the spark electrodes. The electrodes were ground to a cone so that the spark appeared at the center axis of the electrodes. The spark gap width was kept at 1.0 mm at the center of the chamber.

The experimental apparatus is illustrated schematically in Fig. 2. The compression stroke in a four-stroke SI engine was used as a compressor to supply combustible mixtures to the combustion chamber. There are several methods of supplying the mixtures (e.g., using a rapid compression machine or high-compressed mixtures from a mixture cylinder). However, these methods are not useful for many experimental runs, especially for research on determining the minimum ignition energy. The engine used has specifications of 258 cc total stroke volume, one cylinder and compression ratio of 6.5. The mixture was supplied from the cylinder head dividing into four piping lines. The engine was run at the required speed after filling of the combustion chamber, reservoir tank, crank case and piping system with propane-air

Fig. 1 Combustion chamber

Fig. 2 Experimental apparatus

mixture (4.7 vol.%) in the ignition test. The running speed was varied to change the turbulence intensity from 150 to 600 rpm.

The flow rate at the center of the chamber was measured by using a laser Doppler velocimeter (DANTEC 55 X, hereafter referred to as LDV) and hot-wire velocimeter with the constant temperature method (TSUKASA SOKKEN HC-30, wire diameter: 5 μm , length: 1.2 mm) under the air-filled condition in the piping system. Clay powders (mean diameter: 2.0 μm) were used as seeding particles for the LDV system.

The minimum ignition energy was defined as the ignition energy at 50% ignition probability for 30 spark discharges. The ignition timing was 35 deg-CA BTDC. A digital AND circuit was employed to avoid the spark ignition during the exhaust stroke, feeding two signals from an ignition timing sensor and a pressure transducer set on the combustion chamber. In this procedure, the spark ignition occurred exactly at the required timing in the compression stroke.

To take schlieren photographs, the xenon lamp was flashed at 70 μs before ignition timing, avoiding lower exposure in an incipient stage of flashing of the lamp. A high-speed camera was employed to record the flame kernel shape with the framework of 32 000 frames/s, and the exposure duration of 1.5 μs , for each frame. The exposure interval was approximately 31 μs , consequently. The total exposure duration was controlled by flashing duration to avoid double exposures, because the main shutter in the camera was kept open during the access.

The ignition circuit used, as shown in Fig. 3, is based on a capacitor discharge system. The spark produced with this system, however, simulates a composite spark consisting of capacitance and subsequent inductance components. The leading spark corresponding to a capacitance spark is produced with the A-side circuit, and the subsequent one corresponding to an inductance one is produced with the B-side

Fig. 3 Ignition circuit

circuit shown in Fig. 3. Although the subsequent spark simulates an inductance spark, it does not contain a real inductance component generally stored in an ignition coil. Consequently, it is referred to only as the subsequent spark. The performance of the circuit is as follows. The variable capacitor C_2 (100–7360 pF) and C_3 (6600 pF–0.47 μ F) are charged at 10 kV through the charging resistance R_4 and at 800 V through the resistor R_7 , respectively, at the beginning. The breakdown discharge from the C_2 starts between the spark electrodes at the timing of turn on the thyatron Th, feeding the trigger signal into the grid electrode in the thyatron. A short duration capacitance spark, less than 1.0 μ s, appears in this process. The subsequent spark instantaneously starts discharging from C_3 . The diodes D_1 and D_2 play the role of eliminator in interference between the A- and B-side circuits during electric charging or discharging. Both capacitance and subsequent spark energies are able to change independently by varying the capacitance value in C_2 and C_3 , respectively.

The voltage and current waves were recorded on a digital storage oscilloscope (TECTRONIX 2440) through a high-tension probe (TECTRONIX P 6015) and current probe using hole device (TECTRONIX P 6021), respectively. The spark energy was estimated numerically integrating the electric power wave as the products of the voltage and current along the spark duration. The A-side circuit was used to obtain only the capacitance spark, cutting off the B-side one.

3. Experimental Results

3.1 Velocity measurement

An example of velocity measured at the center of the chamber in a compression stroke is shown in Fig. 4. In this case, the engine speed was 600 rpm, and the flow vector measured was aligned with the electrode axis shown in Fig. 1. The flow measured is found to have little mainstream component, though the veloc-

Fig. 4 Typical velocity change at the center of combustion chamber

ity alternately changes in its direction. This fact is confirmed from schlieren photographs, as shown later in Figs. 6 and 7. The classical definitions of turbulence intensity, such as a deviation from the mean velocity of the mainstream, cannot be applied to estimate the intensity, in this case of the non-mainstream condition. Consequently in this study, on the basis of results showing measured velocity itself to be the turbulence intensity, the intensity is defined as the following equation in the same manner as Hamamoto et al.⁽⁹⁾:

$$U' = \{(2U_r^2 + U_z^2)/3\}^{0.5}$$

where U_r and U_z are the velocity components toward the electrode axis and the chamber axis, respectively. U_r was estimated from RMS values in velocity measured by using the LDV system. Regarding U_z , the component was determined in the same manner as described above using a hot-wire velocimeter, since it was difficult to apply the LDV system due to the chamber structure. The ignition tests were performed for four engine speeds of 150, 300, 450, and 600 rpm, and the turbulence intensities for the conditions were 2.53, 3.78, 7.10 and 9.87 m/s, respectively.

3.2 Spark discharge characteristics

The waveforms of voltage and current changes in

(a) Capacitance Component
(Spark energy: 5.19 mJ)

(b) Subsequent Component
(Spark energy: 7.91 mJ)

Fig. 5 Typical voltage and current waveforms of spark discharge

spark discharge are shown in Figs. 5(a) and (b). Figure 5(a) shows a short-duration spark having a capacitance component. Though the voltage and current are oscillating after breakdown discharge, it can be seen to be approximately completed within $0.5 \mu\text{s}$. With increasing capacitance value in C_2 , the amplitude of the current wave increases and the oscillation damps slightly sooner, according to other data obtained. Meanwhile Fig. 5(b) shows a subsequent spark having a long duration as compared with the former. The voltage and current curves change slightly as time progresses; however, it is considered that the electric power as the product of increasing voltage and decreasing current is kept almost constant during the subsequent spark duration.

Increasing capacitance value of C_3 in the circuit means an elongation in subsequent spark duration. Though the current of 270 mA in the incipient stage is fairly large as compared with conventional inductance sparks, the subsequent spark may be a glow spark because of observations such as that the emitted

spark light intensity is weak and the negative electrode is covered by a part of the flame kernel, as will be discussed later.

3.3 Growing shape of flame kernels

Schlieren photographs showing the shape of growing flame kernels produced by the capacitance component alone are shown in Fig. 6. Photographs (a)–(c) show the cases successfully ignited, whereas photo (d) shows a misfiring case. It is confirmed that no mainstream is clearly found because the flame kernel does not blow toward a special fixed direction, its center remaining at the center of the combustion chamber, as shown in all these of cases.

The flame kernels have a toroidal shape at $20 \mu\text{s}$ after spark discharge. Consequently it is considered that the kernels are not affected very much by the turbulence, and follow the same pattern as under a quiescent mixture condition up to that time. From then on, the kernel shown in photo (a) begins to diverge from the toroidal shape, with surface distortion, though expanding normally to the electrode axis.

Fig. 6 Schlieren photograph of flame kernels produced by capacitance spark

In the case of photo (b), though the kernel follows the same pattern as shown in photo (a), the effect of the turbulence appears in an early stage, while the scale of wrinkles on the kernel surface is seen to be smaller as compared with photo (a). In the high-turbulence condition ($U' = 7.10$ m/s) shown in photo (c), the kernel shape is already distorted from the initial toroidal one at $51 \mu\text{s}$, and the wrinkle scale is still smaller than that for photo (b). It is found, consequently, that the effect of turbulence on the flame kernel shape appears in an early stage with increasing turbulence intensity. The turbulence scale can be seen qualitatively becoming smaller with increase in engine speed, even if the scale of wrinkles on the kernel surface does not always correspond to the scale of turbulence⁽⁷⁾.

Meanwhile, in the misfired case shown in photo (d), the flame kernel develops in the same manner as the successfully ignited case until $114 \mu\text{s}$; however

from then on, the kernel spreads over a wide space, and the shading in schlieren photographs gradually fades away. The spatial velocity distribution changes in the combustion chamber for each test run, and as is well known, the turbulence is a statistical phenomenon. Thus, it is considered in the misfiring case as compared with the successfully ignited case that there exists high-intensity turbulence which remarkably expands the kernel or strikingly distorts the kernel surface.

Figure 7 shows schlieren photographs indicating the changing shape of the flame kernel produced by composite sparks, namely adding the subsequent component. By way of comparison, photo (a) showing the growing shape in the quiescent mixture is exemplified. As can be seen in photo (a), the high-temperature region which is not found in Fig. 6 appears at the spark gap and the tip end of the negative electrode. It is considered, in particular, that

(a) Quiescent

(b) Turbulence Intensity: 2.53 m/s

(c) Turbulence Intensity: 3.78 m/s

(d) Turbulence Intensity: 7.10 m/s

Fig. 7 Schlieren photograph of flame kernels produced by composite spark

Fig. 8 Effect of turbulence intensity on minimum ignition energy

Fig. 9 Capacitance and subsequent components under minimum ignition energy condition

the high-temperature region covering the electrode is due to the negative glow. These high-temperature regions play the roles of a heater warming the kernel internally or an insulator keeping away the surrounding cold mixture flowing into the kernel^{(8),(9)}. In the turbulent field, in an incipient stage, the flame kernel develops similarly to the quiescent field, and from then on the kernel expands along the electrode axis as well as normal to the axis, and grows into a massive flame kernel. From the above observation, it is understood that the flame kernel produced by the composite spark has much more ignition ability as compared with that produced by the capacitance component only.

3.4 Ignition property of combustible mixture

The experimental result on the effect of the turbulence intensity on the minimum ignition energy using only capacitance sparks is given in Fig. 8. The mini-

Fig. 10 Effect of subsequent component on total spark energy under minimum ignition energy condition

imum ignition energy exponentially increases with increase in the turbulence intensity. Figure 9 shows the pairing of the spark energy components at 50% ignition probability for various turbulence intensities. The minimum ignition energy for the lower turbulence intensity, as $U' = 2.53$ m/s, could not be estimated, because the ignition probability always rose above the probability of 50% upon addition of only a very little of the subsequent component. It can be seen that the ignition ability is markedly improved by addition of smaller subsequent component to the capacitance one. The addition has a remarkable effect under high-intensity turbulence conditions.

The subsequent component to the total spark energy is shown in Fig. 10, reforming the results given in Fig. 9. As is shown in Fig. 10, it is found that the higher the energy of the subsequent component becomes, the more the minimum ignition energy decreases. Namely under the condition keeping the total spark energy constant, the ignition ability increases with increasing ratio containing the subsequent component to the total spark energy. The above-mentioned results are in good agreement with classical findings on ignition characteristics in SI engines.

4. Concluding Remarks

Experiments on spark ignition under the high-intensity turbulence condition were performed using an ignition system which was able to vary the capacitance and subsequent components independently. On the basis of the schlieren photograph, the growing shape of flame kernels affected by the

turbulence and the spark component is discussed. Measuring the minimum ignition energy, further investigations were made to understand the effects of turbulence intensity and the spark component on the ignition property. The main conclusions obtained are summarized as follows:

(1) In an incipient stage in the spark ignition process, the flame kernel shape is not affected very much by the turbulence. Thus it grows while maintaining a toroidal shape, as in the quiescent condition.

(2) The effect of turbulence on the flame kernel shape appears in an early stage, and the wrinkle scale on the kernel surface becomes smaller with increase in its intensity.

(3) The ignition ability is improved by adding a little of the subsequent component to the capacitance one. The addition produces a marked effect under the high-turbulence condition.

(4) Concerning the spark component ratio, the ignition ability rises with increase in subsequent component to the total spark energy, within the limits of the present work.

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References

- (1) Ballal, D.R. and Lefebvre, A.H., The Influence of Flow Parameters on Minimum Ignition Energy

- and Quenching Distance, Proc. 15th Symp. (Int.) Combust., (1975), p. 1473.
- (2) Kono, M. and Hatori, K., Ignition of Low Flow Velocity Mixtures by Short Duration Sparks, 8th Int. Conf. of Gas Discharges and Their Applications, (1985), p. 500.
- (3) Hamamoto, Y., Ohkawa, H., Yamamoto, H. and Sugawara, R., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 49, No. 444, B (1983), p. 1791.
- (4) Akindele, O.O., Bradley, D., Mak, P.W. and McMahon, M., Spark Ignition of Turbulent Gases, Combustion and Flame, Vol. 47 (1982), p. 129.
- (5) Bradley, D. and Lung, F.K-K., Spark Ignition and the Early Stage of Turbulent Flame Propagation, Combustion and Flame, Vol. 69 (1987), p. 71.
- (6) Kido, H., Wakuri, Y., Ono, S. and Hatanaka, K., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 46, No. 405, B (1983), p. 1016.
- (7) Kido, H., Nakajima, K., Huang, S. and Kitano, K., Studies of Turbulent Flame Structure in Premixed Mixtures, (An Analysis of the Schlieren-photographs of Propagating Flame by a Turbulent Combustion Zone Model), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 55, No. 511, B (1983), p. 882.
- (8) Niu, K., Tsukamoto, T., Ujiie, Y. and Kono, M., Mechanism of Flame Kernel Growth and Effect of Spark Electrode Shapes in Ignition Process by Short Duration Sparks, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 55, No. 511, B (1989), p. 878.
- (9) Ujiie, Y., Niu, K., Tsukamoto, T. and Kono, M., Development of Flame Kernels Produced by Capacitance Sparks in Ignition Process of Combustible Mixtures, JSAE Review, Vol. 10, No. 4 (1989), p. 21.