Effects of Repetitive Spark Discharges with Milliseconds Intervals on the Ignition-to-Flame Propagation Transition for Lean *n*-Heptane/Air and *iso*-Octane/Air Mixtures

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1 Introduction

To reduce carbon dioxide emissions, the improvement of the thermal efficiency of combustors, including spark-ignition (SI) engines, is an urgent task. In SI engines, lean combustion technology is a promising method of improving thermal efficiency. This is because lean combustion improves the theoretical thermal efficiency by increasing the specific heat ratio of the mixture in the Otto cycle and reduces heat loss by decreasing its combustion temperature. On the other hand, it is reported that stable engine operation under lean conditions is very difficult [1, 2]. This is because the Minimum Ignition Energy (MIE), which is the minimum energy required for the ignition-to-flame propagation transition, increases significantly with lean combustion. The increase in MIE in lean combustion engines derives from two main factors: an increase in MIE unique to the mixtures with decreasing equivalence ratio [3–5] and an increase in turbulence intensity to improve combustion velocity [6]. To overcome this difficulty, it is reported that the lean engine operation limit can be extended by repeating the spark discharge every several hundred microseconds using a high-power ignition system [7]. As the other study applicable to the improvement of ignition efficiency, detailed theoretical analysis of the ignition-to-flame propagation transition process of a spherically propagating flame in the quiescent condition has been reported by He [8] and Chen et al. [9, 10]. In the proposed theoretical studies, it is pointed out that the critical flame radius, which leads to autonomous flame propagation, exists in the ignition-to-flame propagation transition process and it has a large impact on the ignition of the mixture.

In this study, we focus on connecting the theory about the critical flame radius and the experiment of repetitive spark discharges (RSD). Focusing on the critical flame radius, it would be possible to ignite the very lean mixture with even smaller energy with RSD. Therefore, the experiments of spherically propagating flame initiated by RSD with milliseconds intervals for quiescent premixtures in the constant volume combustion chamber are performed. To contribute to the development of lean combustion in SI engines, *n*-heptane and *iso*-octane, which are the main components of gasoline fuel and have been

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extensively studied in past research [11, 12] are used as the fuels in this study. The goal of this study is to investigate the ignition-to-flame propagation transition behavior initiated with RSD near MIE conditions.

2 Experimental Method

The schematics of the experimental setup and the appearance of the experimental apparatus are presented in Fig. 1 (a) and (b), respectively. The design of the constant volume chamber is identical to that used in [13]. The combustion chamber system consists of an approximately 25 L internal cavity and counter-rotating fans. A pair of optical observation quartz windows with a diameter of 100 mm is equipped with the chamber. Two opposed stainless-steel electrodes with a tip are placed at the center of the chamber and it is used as a spark ignitor. The diameter of the electrodes is 2.0 mm and the distance between the tips is 3.0 mm.

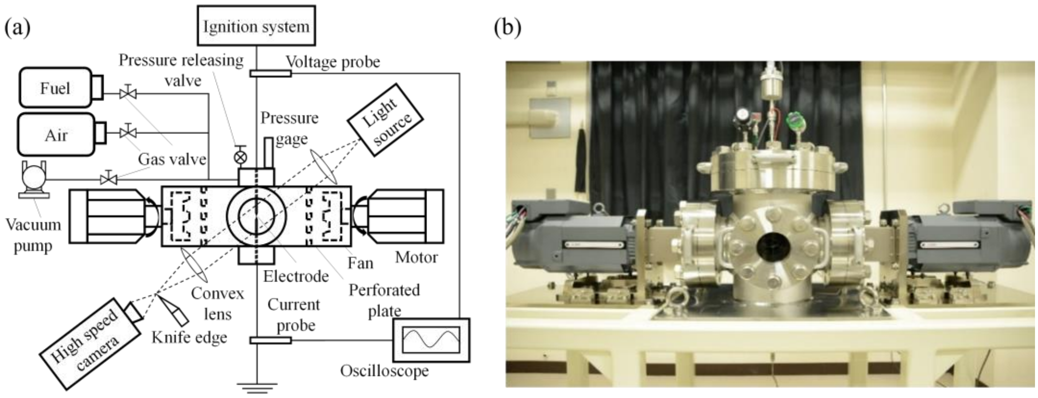

Fig. 1 (a) The schematic diagram and (b) the appearance of the apparatus.

Mixtures of *n*-heptane/air and *iso*-octane/air are made in the combustion chamber by the partial pressure method. The equivalence ratio, ϕ, of each mixture is varied in the range of ϕ = 0.50–0.75 and ϕ = 0.65–0.82, respectively. The initial total pressure, p, and temperature, T, of mixtures are set to p = 0.10 MPa and T = 285±5 K for all experiments.

The spark energy is controlled with a transistor-controlled ignition system device which includes the pulse generator and sets of automotive ignition coils. Two ignition coils are connected in series as a set and up to four sets of ignition coils can be connected in parallel. Pulses generated with a delay generator (DG) are input to the coils, and spark discharges are generated by the induced electromotive force generated by the falling edge of the pulse waves. DG can change the length of a pulse and repeat the input of pulses any number of times. The length of the pulse is changed with the range of 0.5–4.0 ms for a discharge and the spark energy depends on the pulse length. The time histories of the current and

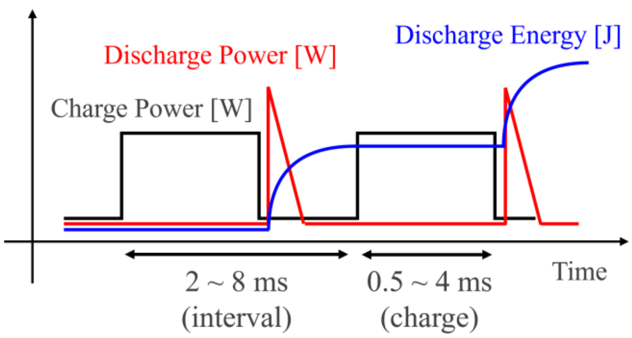

Fig. 2 The schematic of the time history of the electric power and the energy of RSD.

voltage between the electrodes are recorded with an oscilloscope. The input energy is defined as the time-integrated value of the applied electric power from immediately after the discharge. This ignition system can produce a spark with roughly 1–200 mJ. RSD is carried out by repeating the input and cutting the pulse with DG. Figure 2 shows an example of the simplified time history of the electric power of the input pulse and discharges and ignition energy of RSD.

The ignition-to-flame propagation transition processes are observed with a high-speed camera (frame rate: 15,000 fps, shutter speed: 1/300,000 s) with the Schlieren imaging method. The time history of the flame radius is estimated by detecting the flame front in recorded flame images automatically with the function of findContours() from OpenCV (ver. 4.5.5), and the obtained flame radius is used to determine the flame front velocity in the laboratory frame.

3 Results and Discussion

3.1 The results of ignition experiments of lean *n*-heptane/air and *iso*-octane/air mixtures with RSD

To verify the effect of the repetition of discharges with milliseconds intervals on the ignition characteristics, ignition experiments with RSD are conducted for both lean *n*-heptane/air and *iso*-octane/air mixtures. To investigate the effect of the magnitude of energy per discharge on the ignition-to-flame propagation transition process, two groups of RSD are considered: Energy per discharge (EPD) is higher than 100 mJ, which includes very large values around 120–160 mJ, or lower than 10 mJ, which includes very small values around 5-10 mJ. Here, EPD is defined as the quotient of the total repetitive spark energy divided by the number of discharges. To distinguish the EPD from the total discharge energy, EPD will be discussed with a unit of mJ/dcg (dcg: discharge). Experimental results of the two cases of RSD and the case of single discharge are presented in Fig. 3. The horizontal and vertical axes indicate the equivalent ratio of the mixtures and the total input energy of all the repetitive discharges, respectively. The circle and the cross symbols represent the success (Go) and failure (No Go) of the ignition-to-flame propagation transition, respectively. The black symbols show the results obtained by a single discharge, while the blue and red symbols represent results obtained with RSD in the cases of EPD > 100 mJ/dcgand EPD < 10 mJ/dcg, respectively. The dashed lines in the figures show the approximate boundaries between success and failure of ignition.

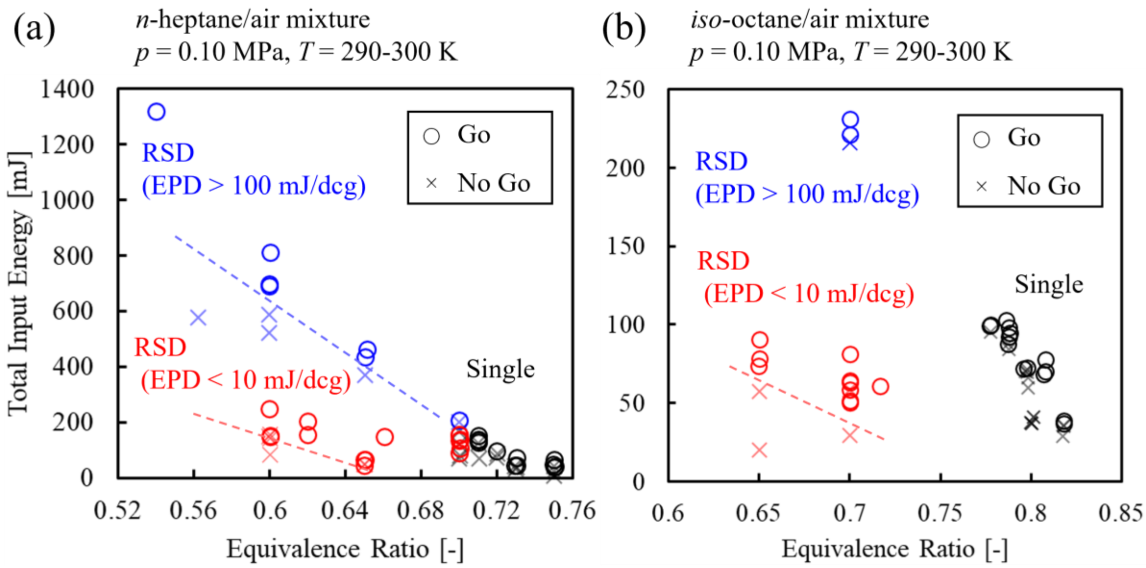

Fig. 3 The change of the total input energy and ignitability for (a) *n*-heptane/air mixture at equivalence ratio 0.52 < ϕ < 0.76 and (b) *i*-octane/air mixture at 0.60 < ϕ < 0.85, with the different ways to discharge.

Firstly, in the case of single discharge shown in black plots, the ignition-to-flame propagation transition is successful down to ϕ = 0.71 for the *n*-heptane/air mixture, as seen in Fig. 3 (a). The minimum input energy required for the ignition-to-flame propagation increases with decreasing equivalence ratio. Note that the input energy for one discharge is available up to about 200 mJ because of the experimental limitation. As with the *n*-heptane/air mixture, the minimum input energy required for successful ignition for the *iso*-octane/air mixture increases with decreasing the equivalence ratio as seen in Fig. 3 (b).

Secondly, in the case of EPD > 100 mJ/dcg with RSD shown in blue plots, the ignition-to-flame propagation transition is successful down to ϕ = 0.54 for the *n*-heptane/air mixture. When ϕ = 0.54, the discharge with a time interval of 6.0 ms is repeated 7 times and the total input energy attains nearly 1300 mJ. Compared to the case of a single discharge, RSD can ignite the lean mixture with a very low equivalence ratio at which it is impossible to ignite with a single discharge.

Finally, in the case of EPD < 10 mJ/dcg with RSD shown in red plots, as with the case of EPD > 100 mJ/dcg, ignition at the very low equivalence ratio down to ϕ = 0.60 is confirmed. Furthermore, it is noteworthy that the total energy required for ignition in the case of EPD < 10 mJ/dcg is significantly smaller than that in the case of EPD > 100 mJ/dcg. For example, at ϕ = 0.60, the minimum total energy required for ignition-to-flame propagation transition is 148 mJ with EPD = 5.9 mJ/dcg, which is attained with 25 times repetition of discharges with a time interval of 3.0 ms, resulting in a total energy input duration of 75 ms. On the other hand, the minimum total energy is 691 mJ in the case of EPD = 173 mJ/dcg for 4 times discharges with a interval of 6.0 ms, with a total energy input duration of 24 ms. The same trend that ignition-to-flame propagation transition occurs with small total input energy in case of EPD < 10 mJ/dcg is also confirmed for *iso*-octane/air mixtures. Note that the two cases with RSD are different greatly from the time to complete the energy input into the flame kernel, which depends on the number of discharges. From these results, not only the amount of the total input energy but also EPD and the time to complete the energy input have a huge impact on the extension of the lean ignition limit and the ignition-to-flame propagation transition process.

3.2 The comparison of ignition-to-flame propagation transition processes with the single spark discharge and repetitive spark discharge.

To investigate the difference in the total energy required for ignition with varied EPD, the time histories of the flame radius and the flame front velocity are obtained from the recorded video images. Figure 4 (a) shows the relationships between the flame radius and the flame front speed in the ignition-to-flame propagation transition for *n*-heptane/air mixture at ϕ = 0.71 in the case of single discharge and RSD. In Fig. 4 (a), the blue and red dots indicate the case of success and failure for ignition-to-flame propagation transition with single discharge, respectively, and the green dots show the case of success with RSD in the case of 10 discharges with EPD = 7.2 mJ. White circles on the green dots are the plot at which the repetitive discharges occur. Figure 4 (b) is a simplified conceptual schematic of the results of Fig. 4 (a). When input energy, Q, is lower than MIE with a single discharge, the flame kernel does not reach the critical flame radius, R_{cr}, as shown with red curves in Fig. 4 (b). On the other hand, repetitive discharges, even if Q is less than MIE, are likely to provide additional energy and gradually expand the flame radius. Eventually, it reaches the critical flame radius with RSD. However, the clear reason why a smaller EPD significantly reduces the total energy required for ignition remains uncertain.

Chen et al. performed detailed analysis of the ignition-to-flame propagation transition process for a spherically propagating flame in a quiescent premixture, as in this experiment, and the experimental results with single discharge agree in general with the proposed analysis. In their recent work, they analytically pointed out that MIE decreases with an increasing number of divisions of the energy input pulse, i.e., when the number of repetitions of the energy input pulse increases and the amount of the energy per pulse decreases, the MIE decreases [14]. They concluded that it is because of an effect of flame behavior called the memory effect [15]. The experimental results of the present study show a

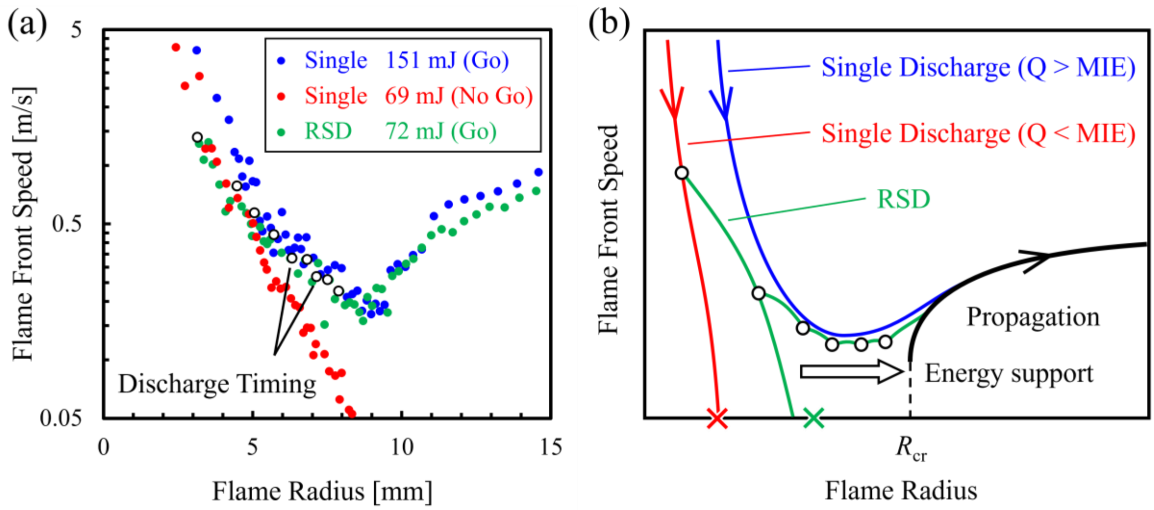

Fig. 4 (a) The experimental result and (b) the conceptual schematic of flame front speed as a function of flame radius in the ignition-to-flame propagation transition process for *n*-heptane/air mixture at ϕ = 0.71 with single spark discharge and RSD.

similar tendency, however, the degree of the decrease in MIE with smaller EPD is different greatly from the results in [14].

As a future work, we believe that DNS that takes into account the effect of the time to energy input, the temperature of the spark, and chemical reactions will contribute to understanding the mechanism.

4 Conclusions

To investigate the effect of the repetitive spark discharge (RSD) in millisecond order on the ignition-to-flame propagation transition, ignition experiments of spherically propagating flame with lean quiescent premixtures for *n*-heptane/air and *iso*-octane/air at room temperature and atmospheric pressure are performed, and the following findings are obtained.

- RSD with EPD > 100 mJ/dcg enables successful ignition at lean conditions for *n*-heptane/air mixture at ϕ = 0.54–0.70, and the total energy required for ignition increases linearly with decreasing equivalence ratio. Moreover, RSD with small energy per discharge (EPD), EPD < 10 mJ/dcg, also achieved successful ignition at the lean condition at ϕ = 0.60–0.70.
- Compared to the RSD with large energy (EPD > 100 mJ/dcg), RSD with small energy (EPD < 10 mJ/dcg) decreases significantly the total energy required for the ignition of the *n*-heptane/air mixture. Likewise, with the *iso*-octane/air mixture, the same tendency is confirmed. Since the time to complete the energy input varied with different EPD, the amount of energy and the time for energy input are likely to have a great impact on the ignition-to-flame propagation transition.
- Comparing the experimental results of the ignition-to-flame propagation transition process using single discharge and RSD, it is indicated that the flame radius gradually increases with RSD in the ignition process, which results in the critical flame radius. The effect of EPD on the total amount of energy required for ignition needs further investigation.

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