Effects of Discharge Frequency on Ignition Behaviors of DBD for Lean Methane/Air Mixtures

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1 Introduction

In order to increase the flame propagation speed, turbulence with swirl and tumble flows is introduced into the combustor of spark ignition engines for lean combustion. In such environments, it is difficult to ignite the mixture. Therefore, an improvement to the ignition performance for lean and diluted mixtures is required to increase the thermal efficiency of engines. Although electric spark ignition has been used widely for conventional automobile engines, high spark energy is required to enhance the ignition performance of the electrical spark ignitions for lean mixtures, resulting in damage to the electrode and large heat loss. Thus, novel ignition methods as with laser breakdown spark ignition [1], repetitive short pulse ignition [2], microwave plasma assisted ignition [3], low temperature plasma ignitions [4,5] have been tested to establish a high-performance ignition method. In the present study, we focus on the low temperature plasma ignition using a dielectric barrier discharge (DBD). Plasma assisted combustion [6,7] have been tested to enhance the reactivity of the mixture and increase the flame speed. For this purpose, low temperature plasma discharge has been used to form radicals, excited molecules and electrons, resulting in the increase in the reaction rates. The enhancement of chemical reaction rates using plasma-assisted combustion are achieved by the combination of the thermal effects and chemical effects, which is strongly related to the plasma conditions. Most combustion studies on plasma-assisted combustion have been conducted at low pressure where low temperature plasma can be formed easily. However, the mixture is ignited at high pressure in engine condition, and the understanding on the low temperature plasma formations under such environment is rather limited. In the present study, ignition experiments of DBD at high pressure are conducted in order to obtain fundamental knowledge on the ignition characteristics of the low temperature plasma, high temperature plasma and their plasma formation processes. Ignition characteristics in a quiescent condition are also investigated experimentally after clarifying the condition where the low temperature plasma is formed.

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2 Experimental

A schematic of the experimental setup is shown in Figure 1. Ignition experiments were performed in a combustion chamber with a constant volume. The combustion chamber has several flanges with quartz glass. Through an optical window, discharge processes were observed using a high-speed video camera (Vision Research, Phantom V2511) with the flame speed of 50000 fps. Methane/air mixtures were prepared in a mixture tank with a stirrer. The equivalence ratio tested in the present study was less than 0.6. Three pressure transducers (KEYENCE, AP-33, AP-30 and AP-14S) were installed to the tank and the concentration of the mixture was determined from the partial pressure of the components. For a condition, the same mixture was introduced to the chamber and ignition tests were conducted. A spark plug was mounted on a flange of the wide wall, and the central electrode was insulated by a ceramic, which regulates the amount of the current and makes it possible to form the DBD. Streamer was formed between the central electrode and the outer electrode. The spark plug was connected to a high-voltage and high-frequency AC power supply. The primary AC current was input into the circuit with a coil and amplified at the resonant frequency. The frequency of the current was adjusted by changing the coil of circuit. The maximum output voltage of the power supply was ±40kVp-p. In the present study, frequencies of the current were 600, 800 and 1030kHz, and two input signals of the circuit were produced by a pulse generator (BNC, 555), which control the burst period and the driving frequencies. Using this system, the number of the current pulses applied to the plug can be controlled.

Characteristics of DBD were investigated in air at various pressures from 10 to 2500kPa at room temperature. In this case, the primary voltage of the alternate current was fixed to 120Vp-p. The streamer formations were observed using the high-speed video camera, and the lifetime of plasma emissions was evaluated. Thereafter, ignition experiments were performed at 100kPa for methane/air mixtures. The effects of the frequency of the output alternate current on the lean limit were investigated.

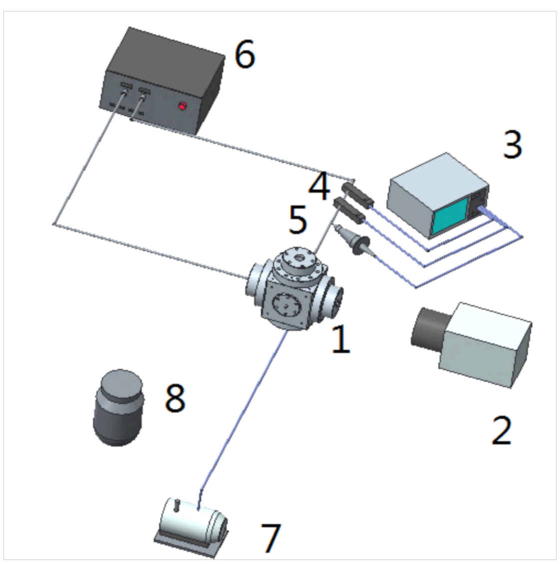

Figure 1. Schematic of experimental setup.
1.Combustion chamber, 2. High speed video camera, 3. Oscilloscope, 4. Current probes, 5. High voltage probe, 7. Vacuum pump, 8. Mixture tank

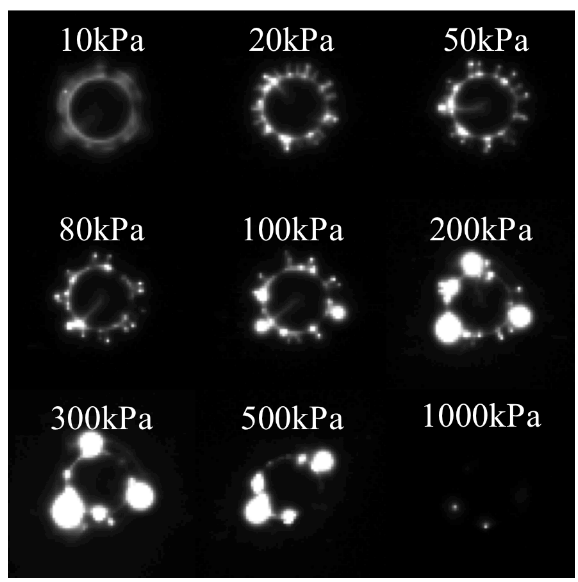

Figure 2. Instantaneous images of DBD at various pressure.

3 Results and Discussions

Firstly, the effects of the pressure on DBD were investigated. Figure 2 shows the instantaneous images of DBD measured by a high-speed video camera at various pressures. In this figure, the exposure time of the high-speed video camera was ranged from 4.5 to 19.5μs. Thus, multiple discharges at different timings were recorded on one image because high-frequency alternate voltage was applied. It seemed that one discharge was achieved for nanoseconds. The primary voltage of the circuit was 120Vp-p in this case, and the discharge frequency was 640kHz. The discharge period was 1.0ms. It is noted that no streamer formations were observed for the primary voltage of 120Vp-p over 1000kPa. It can be seen that the number of streamers increases with a decrease in the pressure. Above 200kPa, the strong emission of the plasma kernel was observed locally between the electrodes. At high pressure over 100kPa, low temperature plasma of the streamer discharge could change to thermal equilibrium plasma. Starikovskaia has shown that streamer discharges are observed for the applied voltage of 10 to 100kVp-p at 0.01 and 0.1 MPa [4]. For results in Figure 2, the voltage was applied from 25 to 35kVp-p and this tendency was confirmed.

Figure 3 shows emission periods of plasma at various pressures. In figure 3, emission periods for the primary voltage of 150Vp-p are also plotted. In the case of 150Vp-p, discharge was observed even at 3000kPa although no discharge was observed in the case of 120Vp-p. It can be seen that emission periods were approximately 1ms at the pressure of 100kPa or less, which is equal to the discharge duration of current. When the pressure was over 100kPa, the plasma lifetime was greater than the discharge duration, indicating that the thermal equilibrium plasma was formed. In the case of 150Vp-p, the applied voltage was ranged from 35 to 40kVp-p. An increase in the applied voltage resulted in the extension of the upper limit of pressure for discharge. However, the period of plasma emission increased with ambient pressure. Active plasma was formed for 150Vp-p, and the plasma lifetime became longer with an increase in the pressure. Although the discharge time was 1ms, plasma emission was observed for 15ms. Even after the discharge, plasma seemed to exist and high temperature was sustained.

From the experimental results above, low temperature plasma could be formed at 100kPa or less. In order to investigate the effects of the DBD frequency on ignition performance, ignition experiments were conducted for lean methane/air mixtures at 100kPa and 50kPa. The applied voltage to the electrode was fixed to 35±1KVp-p and the discharge period was 1ms. The frequency of the alternate current was varied to 600, 800 and 1030kHz. For one condition of the equivalence ratio, 10 runs of discharge were conducted. Figures 4 and 5 show relationships between ignition probability and the equivalence ratio of the mixture at 100kPa and 50kPa. It can be seen that the lean limit was extended with an increase in the discharge frequency. Since the discharge period was fixed to 1ms in this case, higher frequency resulted in more

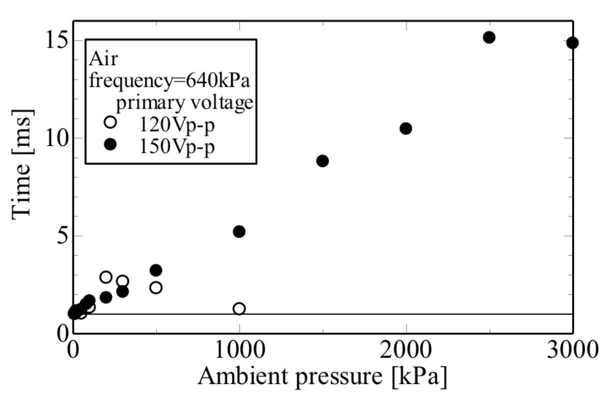

Figure 3. Relationship between period of plasma emission and ambient temperature.

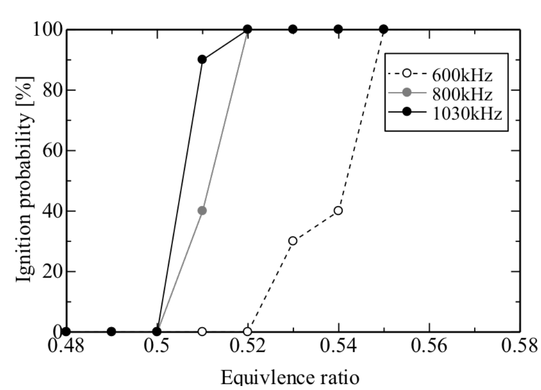

Figure 4. Ignition probability for methane/air mixtures at 100kPa.

discharge counts. Therefore, applied energy to the mixture was higher, resulting in the extension of the lean limit. At 50kPa, successful ignitions were observed even less than the equivalence ratio of 0.5. The lean limit of the equivalence ratio at 50kPa was less than that at 100kPa. This could be due to the induced flow by the buoyancy. Induced flow velocity becomes higher with an increase in the density, and this slight flow fields seemed to inhibit the ignition [8].

Ignition experiments were also conducted for lean methane/air mixtures under the same count of the discharge pulse. The discharge durations for 600kHz, 800kHz and 1030kHz are 1.7167, 1.2875 and 1.0000 ms, respectively. Figure 6 shows ignition probability at 50kPa and 100kPa for methane/air mixtures with the equivalence ratio of 0.5. Ignition characteristics near the lean limit were investigated. Even under the same condition of the discharge counts, the ignition probability became higher with an increase in the discharge frequency. For 600 kHz, no ignition was observed as shown in Fig. 6 although leaner mixtures were ignited in the case of 1030 kHz as can be seen in Fig. 5. In the case of 800 kHz, no ignition was observed for the discharge duration of 1ms. However, an increase in the discharge duration to 1.2875ms made it possible to ignite the mixture. In addition, high frequency discharge resulted in the increase in the ignition performance. In this case, plasma reaction occurs during the current discharge between the electrodes. Discharges seemed to occur during the short period of nanoseconds, and the electrons were absorbed by ions during the rest time. When the frequency became higher, electrons might be still alive when the next discharge occurred. In this case, electron productions are accelerated, resulting in the further production of active radicals. Therefore, high-frequency discharges seem to show the better ignition performance.

4 Conclusions

A discharge and an ignition processes of the DBD were investigated in a combustion chamber with a constant volume. As a result of this study, conclusions below were obtained.

1. Low temperature plasma was formed at 100kPa or less using the ignition system of this study.
2. Plasma lifetime is longer than the discharge period with an increase in the ambient pressure for the same primary voltage.
3. For the same discharge period of 1ms, higher discharge frequency resulted in better ignition performance.
4.Even under the same discharge counts, higher discharge frequency resulted in better ignition performance.

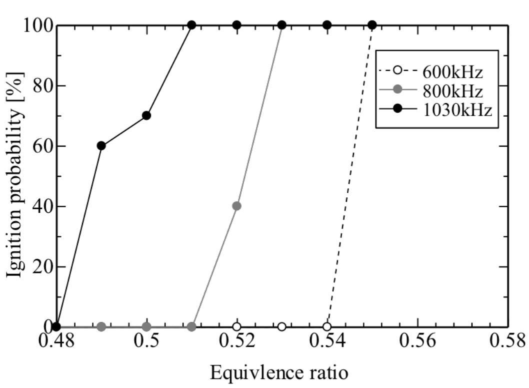

Figure 5. Ignition probability for methane/air mixtures at 50kPa.

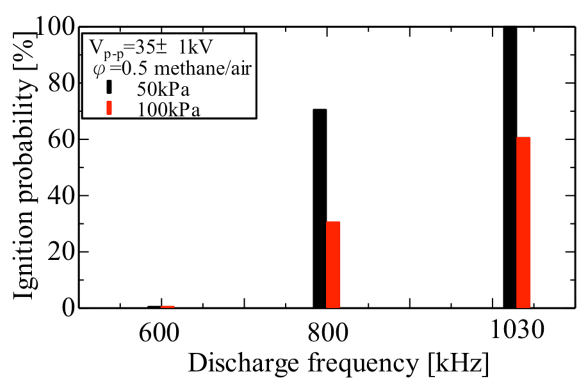

Figure 6. Ignition probability for methane/air mixtures with the equivalence ratio of 0.5 under the same discharge counts.

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