Effects of Superposition of the Dierectric Barrier Discharge on Methane/air Laminar Lean Premixed Flame

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1 Introduction

Combination of the combustion and plasma has been investigated with a purpose of the enhancement of combustion processes [1-11]. Straikovskaia reported a review of this field including basic mechanisms of plasmas [1]. Because of possibilities of the enhancement of combustion processes, a lot of researches have been reported using a variety type of plasmas [1]. Especially, the non-equilibrium plasma was adopted as the plasma source in order to avoid effects of increase of the gas temperature on the combustion reaction [2-11]. Effects of non-equilibrium plasma on the combustion phenomena have been investigated in terms of the improvement of ignitibility [2-4] and the enhancement of combustion processes [2, 6-9]. Strakovskii investigated the influence of gas excitation by a pulsed nanosecond discharge on the properties of a propane/air premixed flame [2] and showed the blow-off limit of the flame was expanded by a plasma discharge. Ombrello et al. investigated effects of the additional molecular of ozone, which is provided by the dielectric barrier discharge (DBD) on unburned oxygen, in a combustible mixture on the burning velocity and a stability of the flame [8,9]. They indicated that the presence of ozone in an unburned combustible mixture affected to increase the burning velocity and to make the flame stable. DBD is one of the non-equilibrium plasma, and it can be easily understood from those reports that DBD has a potential to enhance the burning velocity. However, since DBD discharged on the unburned premixed gas or oxygen, it is difficult to understand effects of DBD on the combustion reactions in flame in detail. To understand effects of superposition of DBD on the flame in detail, it is effective to investigate those influences in the stable laminar premixed flame [12].

In this study, therefore, the enhancement of combustion processes of laminar premixed flame by non-equilibrium plasmas was experimentally investigated through a discharge of DBD on the combustion region of methane/air laminar premixed flame under atmospheric pressure. Since it is known that the properties of DBD are affected by characteristics of a power source, effects of the frequency of the power source of DBD on a laminar premixed flame was investigated. To clarify effects of superposition of DBD on the combustion region of methane/air laminar premixed flame, high-speed imaging and time-series measurement of chemiluminescences of OH* and CH* were conducted in this study.

2 Experimental Apparatus and Conditions

Figure 1 shows the schematic illustration of the experimental setup. Table 1 shows the experimental conditions of this study. Methane/Air premixed gas was used as the combustible mixture. Flow rates of fuel and oxidizer were controlled individually using mass flow controllers and gases were premixed in the inline static mixer before supplying to the burner. The premixed gas of methane/air was supplied to the burner. The premixed gas was commuted through the sintered metal, a metal mesh, a ceramic honey comb and a contraction throat.

To observe the flame structure and the effects of superposition of DBD on the combustion region of methane/air laminar premixed flame, a slot burner was utilized. This burner can make the stable laminar premixed flame where the laminar burning velocity can be measured precisely because the flame shape is like a "triangle pole" without the distribution in the depth direction of triangle pole. The slot burner had two parts. One was the body of the burner and the other was the barrier for DBD. Both parts were made by glasses. The exit port of slot burner was the rectangular shape of 8 mm and 40 mm. In order to form DBD, an electrode was attached outside of the middle of the barrier glasses. The height and width of the electrode were 8 mm and 40 mm, respectively. The gap between two barriers was set at 11 mm. The power source system was composed of a function synthesizer, a continuous sinusoidal wave AC source and an amplifier. The voltage and frequencies of power source were controlled at 28 $kV_{p\text{-}p}$ and 200, 1000, 7000 Hz. Direct observation and time-series measurements of chemiluminescence were conducted to the flame stabilized at the exit of slot burner. Direct observation and CH* chemiluminescence images were conducted using high-speed CMOS camera (Phantom V12.1, Vision Research Inc.) to calculate the flame height. The area of high speed imaging was set at 5.5 mm width and 30 mm height, and the spatial resolution was 147.5 μm/pixel. Figure 2 shows the measurement point of the chemiluminescence. In addition, time series of chemiluminescences of OH* and CH* were measured using the Multi-color Integrated Cassegrain Receiving Optics (MICRO) [12] and photomultiplier with band-pass optical interference filters (central wavelength = 306.6 nm, half bandwidth = 9.3 nm for OH*, and central wavelength = 431.1 nm, half bandwidth = 3.0 nm for CH*). The measurement point of OH* and CH* chemiluminescence was positioned at 8.7 mm height above the burner, 1.9 mm from the center of the burner and the depth of measurement point was 30 mm from the front edge of slot burner. In the experiments, the time-series data of chemiluminescence of OH*, CH*, the discharge current and voltage were recorded by high-speed AD converter.

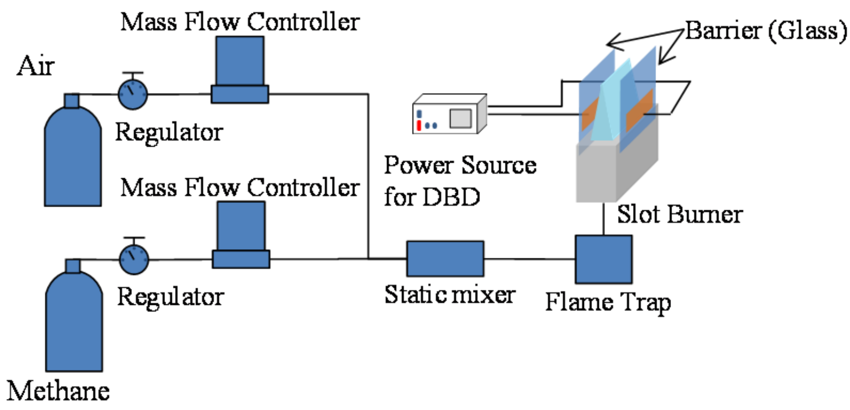

Fig. 1 Schematic illustration of experimental apparatus

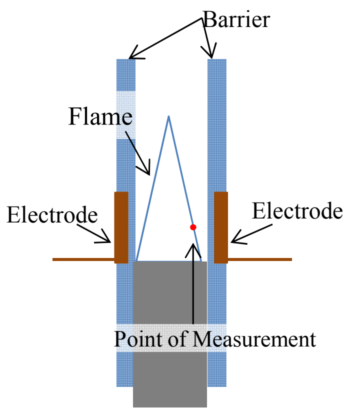

Fig. 2 Schematicl illustration of burner

Table 1 Experimental conditions

Flame condition	Equivalence ratio	0.75
	CH_4 [L/min]	1.2
	Air [L/min]	15.8
	Flame height [mm]*	17
Discharge condition	Voltage [kV_{p-p}]	28
	Frequency [Hz]	200, 1000, 7000

* measured without DBD

3 Results and Discussion

Figure 3 (a) ~ (d) shows the direct photograph of the laminar premixed flame. The frame rate and exposure time of the high speed imaging were (a) (b) 3000 fps, (c) 10000 fps, (d) 20000 fps, respectively. The equivalence ratio of the flames was set at 0.75 as shown in Table 1. Figure 3 (a) shows the direct photograph of the premixed flame without DBD. It is found from Fig. 3 that the flame shape was deformed by the superposition of DBD, and the degree of deformation was affected by the frequency of the power source. In conditions of high frequency ((c)1000 Hz and (d) 7000 Hz), the deformation of the flame did not appear as shown in Fig. 3. It can be thought that this is because the flame deformation cannot follow the frequency of power source.

Here, heights of the flame from the burner exit port were calculated using ensemble average of 1000 frames of high speed CH* chemiluminescence images taken by high-speed CMOS camera. Those values were 14.0 mm, 13.6 mm, 12.5 mm. The laminar burning velocity (S_u) was obtained by Eq. (1) in this study,

$$S_u = \frac{1000U}{60S} sin\left(tan^{-1}\frac{L}{2H}\right) \tag{1}$$

where, mass flow rate, cross section area of burner port, length of the burner and flame height obtained from CH* chemiluminescence image were indicated as U [L/min], S [cm^2], L [mm] and H [mm], respectively. The obtained laminar burning velocity S_u were (a) 23.8 cm/s, (c) 25.1 cm/s, (d) 27.0 cm/s, and the increase ratio of $\Delta S_{u\_withDBD}/S_{u\_withoutDBD}$ were (c) 5.18 %, (d) 13.2 %, respectively. Those results indicated that the laminar burning velocity obtained by using flame height was increased with the superposition of DBD. In addition, the increase ratio of S_u increased with increasing the frequency of power source of DBD.

Since it can be supposed that the laminar burning velocity increases with increasing of the molar fraction of chemical carrier, it needs to understand the effects of superposition of DBD on the combustion reaction. Although it is difficult to connect directly with the molar density and the intensity of chemiluminescence, time series of the chemiluminescences of OH* and CH* with/without DBD were measured in this study for understanding the effects of superposition of DBD on the flame. Figure 4 shows the time-series data of voltage, current, chemiluminescences of OH* and CH* without DBD. Figure 5 shows the time-series data of voltage, current, chemiluminescence of OH* and CH* signal with DBD of 200 Hz, 1000 Hz, 7000 Hz. It is found from Fig. 4 that the stable OH* and CH* signal is obtained in the condition without DBD. This means that the premixed flame is stable. In the frequency of 200 Hz, OH*, CH* signal is fluctuated as showed in Fig. 5. This is because that flame is deformed by the electric field, as mentioned in the section of direct observation. On the other hand, the spike signals of OH* and CH* were observed in the condition of high frequency and those spike signals of OH* and CH* appeared at the same time of the spike signals appeared in the current. The spike signals appeared in the current indicated that the streamer discharges were generated by DBD. It can be thought from those results that the increase of the laminar burning velocity depends on the superposition of the streamer discharge generated by the DBD on the laminar flame.

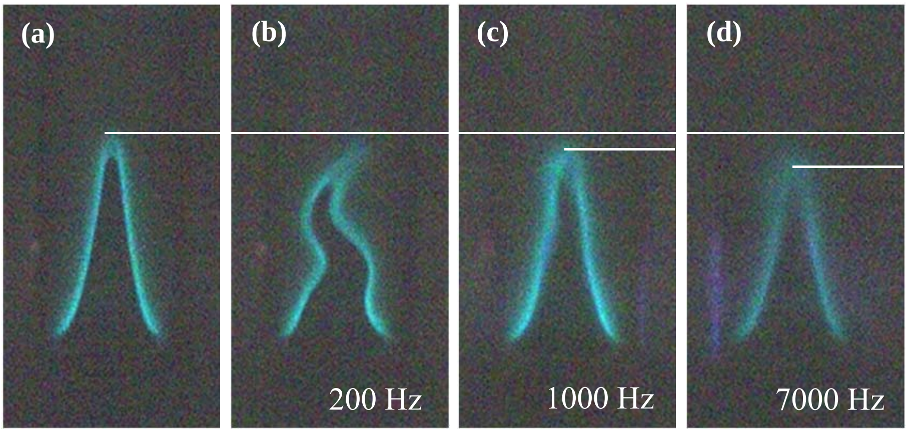

Fig. 3 Direct photographs of laminar premixed flame without DBD (a) and with DBD of (b) 200 Hz, (c) 1000 Hz, (d) 7000 Hz

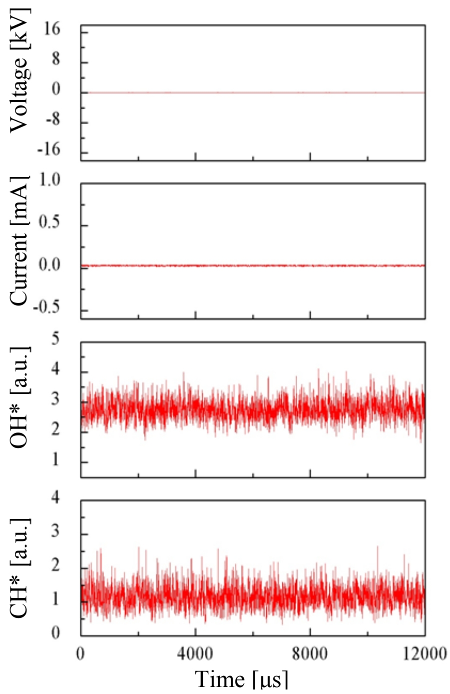

Fig. 4 Time series of voltage, crrent and chemiluminescences OH* and CH* without DBD

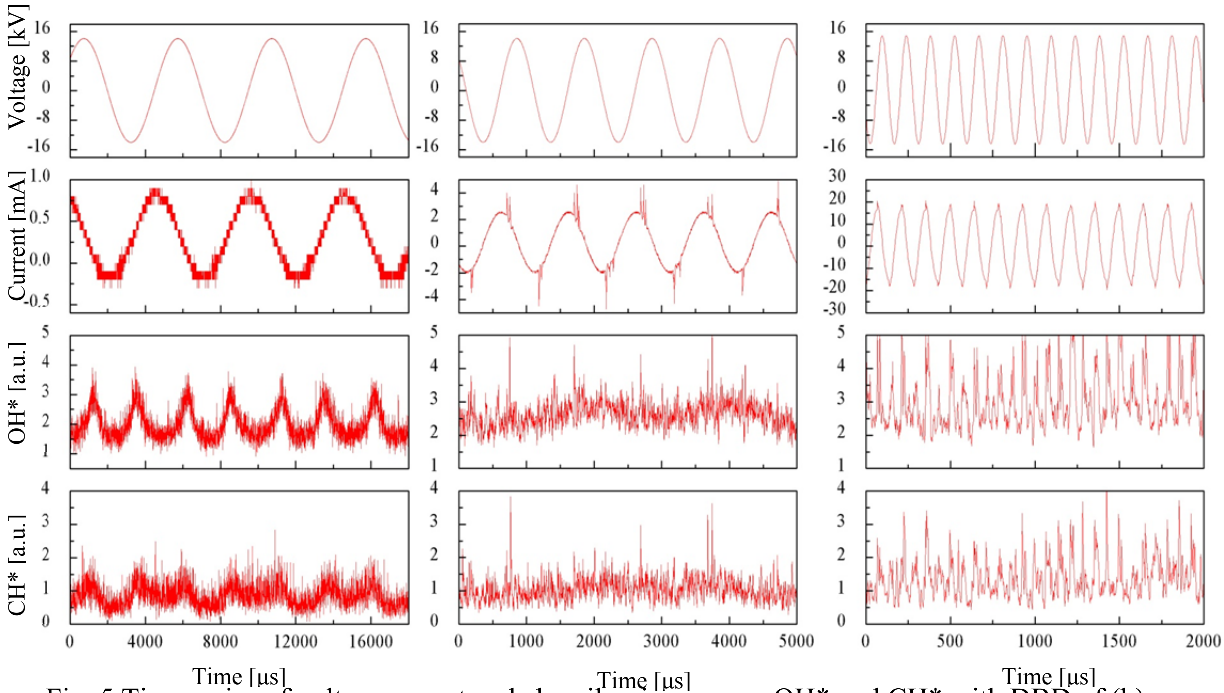

Fig. 5 Time series of voltage, crrent and chemiluminescences OH* and CH* with DBD of (b) 200 Hz, (c) 1000 Hz, (d) 7000 Hz

4 Conclusions

To understand effects of superposition of dielectric barrier discharge (DBD) on the combustion field in detail, DBD discharged in the laminar combustion region of methane/air premixed flame at atmospheric pressure. Results show that laminar burning velocity obtained by using flame height increased with superposition of DBD and the degree of improvement enhanced with increasing frequency of power source of DBD. In addition, intensities of chemiluminescence of OH* and CH* increased steeply at the same time of the streamer discharge generated by DBD. The spike signals also appeared in the current. This result indicated that the streamer discharges were generated by DBD at the moment of spike signals. Those results suggest that the increase of the laminar burning velocity depends on the superposition of the streamer discharge generated by the DBD on the combustion region of laminar premixed flame.

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