Behavior of Chemically Active Species in a Premix Burner using a Dielectric Barrier Discharge Plasma Actuator

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Abstract

A coaxial dielectric barrier discharge plasma actuator (DBD-PA) with electrodes installed inside a dielectric nozzle was used to assist combustion in burner premixed combustion. First, plasma was generated in a laminar flame of a premixed gas of propane and air. As a result, it became possible to continue combustion by generating plasma even at low equivalence ratios where the blow-off phenomenon would normally occur. The following three factors can be considered for assisting combustion: diffusivity due to the flow induced by DBD-PA, combustion promotion due to the generation of chemically active species, and increased stability of the flame base due to the weak ionization state within the combustion flame and electrostatic discharge. To identify the chemically active species, we used emission spectrometry and absorption spectrometry. The purpose of this study was to clarify how the induced flow generated by plasma and the generation of chemically active species by plasma contribute to combustion. We were able to confirm an increase in chemically active species at applied voltages of 12 kV to 16 kV.

Keyword: *Premixed combustion control, DBD-PA, Emission spectroscopy, Absorption spectroscopy*

1. Introduction

Plasma-assisted combustion has been extensively studied, including research on controlling combustion through the superposition of discharge plasma and flame, and research on improving the ignitability of fuel using plasma. Superimposing high-frequency thermal plasma on a premixed oxygen combustion burner flame has revealed that high-frequency power contributes to promoting the combustion reaction. Furthermore, it has been shown that when a low-frequency, high-voltage discharge is superimposed on a premixed combustion burner flame, the behavior of active combustion species may be affected by electrostatic discharge [1]. In the basics of dielectric barrier discharge (DBD) and its application to combustion control, by generating DBD in the combustion premixture in a cylinder, O atoms generated in the initial reaction process interact with H atoms extracted from hydrocarbons. From this, it was shown that alkyl radicals and hydroxyl radicals are generated [2]. In this study, we attempted to enhance burner premix combustion using a coaxial DBD plasma actuator (DBD-PA) with an electrode installed in a nozzle made of dielectric material. First, a plasma was generated in a laminar flame of a premixture of propane and air. This technique made it possible to continue combustion by generating plasma even at low equivalence ratios where the blow-off phenomenon would normally occur. The following three factors can be considered for assisting combustion: diffusivity due to the flow induced by DBD-PA, combustion promotion due to the generation of chemically active species, and enhanced stability of the flame base due to the weak ionization state within the combustion flame and electrostatic discharge. To identify the chemically active species, we used emission spectrometry and absorption spectrometry. The purpose of this study was to clarify how the induced flow generated by plasma and the generation of chemically active species by plasma contribute to combustion.

2. Experiment

A coaxial type DBD-PA was placed at the tip of a convergent nozzle with an outlet diameter of d = 6 mm to form a combustion burner (Figure 1). An AC rectangular voltage was generated by a function generator, amplified 2000 times, and then supplied to the actuator. When voltage was applied, DBD plasma was generated on the inner wall surface of the nozzle exit. This created an induced flow that caused velocity changes and created active chemical species in the fuel, which affected the flame. The electrodes of DBD-PA are made up of three parts: top, bottom, and center. In Case A, flow was induced in the direction along the main stream by the upper and center electrodes, and in Case B, flow was induced in the direction against the main stream by the lower and center electrodes. We could switch between A and B. We compared flame shapes using a high-speed camera, measured the effects of plasma-induced flow using a hotwire anemometer, investigated whether chemically active species increased using a small spectrometer, and measured the ozone concentration using a detection tube. The experimental conditions were that propane and air were premixed and supplied in the range of Q = 3.31±0.01 L/min (~1.95 m/s), and the mixture was mixed and ignited so that the equivalence ratio varied from φ = 0.80 to 1.10, the applied frequency f = 4 kHz, and the applied voltage $V_{P\text{-}P}$ = 0 kV to 16 kV.

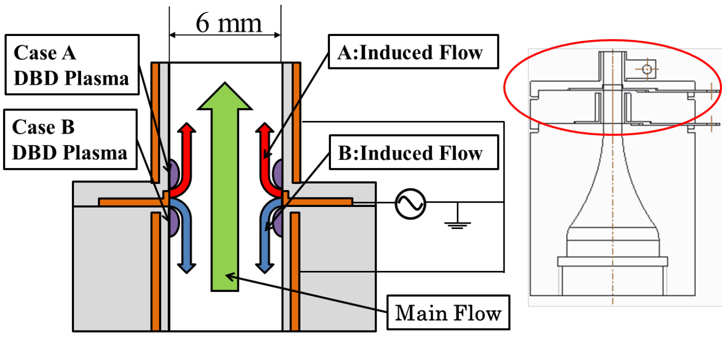


Fig. 1 Flame control by induced flow with DBD-PA

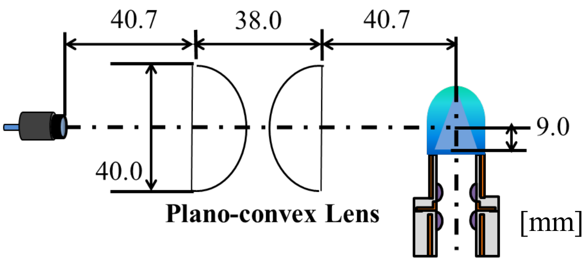


Fig. 2 Optical system for flame emission spectroscopy

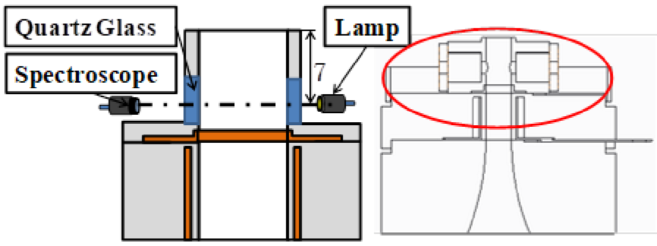


Fig. 3 Optical system for absorption spectroscopy

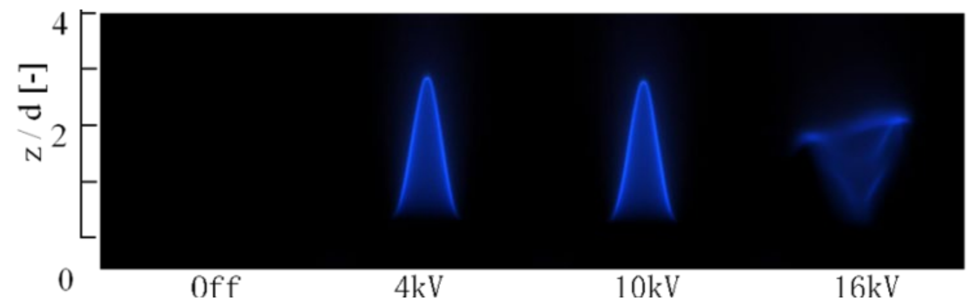
Figure 2 shows the setup for measuring chemically active species using a spectrometer. Two plano-convex lenses were used to collect the spontaneous light emitted by the flame and plasma, and an optical fiber was installed at the focal point to guide the light to the spectrometer. At an equivalence ratio of φ = 1.10, the applied frequency f = 4 kHz was constant, and the applied voltage $V_{P\text{-}P}$ was increased from 2 kV to 16 kV in increments of 2 kV. The measurement conditions were an accumulation time of 40 ms and an average of 20 times for 300 ms. Dielectric barrier discharge is known to generate ozone, which acts as an oxidizer and is thought to promote combustion, so the ozone concentration was measured. The equivalence ratios were φ = 0.80, 0.95, and 1.10; the applied frequency f = 4 kHz was constant for air; and the applied voltage $V_{P\text{-}P}$ was increased from 2 kV to 16 kV in increments of 2 kV. Gas was collected using a sampling bag, and the ozone concentration was measured using a detector tube. Furthermore, to perform absorption spectroscopy, a nozzle with an opening near the plasma generation part and attached quartz glass was used (Figure 3). For the absorption spectroscopy, plasma was generated in two states: unburned mixture and flame combustion. The applied frequency f = 4 kHz was constant, and the applied voltage $V_{P\text{-}P}$ was increased in 2 kV increments from 2 kV to 16 kV. Deuterium, tungsten, and halogen lamps were irradiated from the quartz glass, passed through the inside of the nozzle, and led to the spectrometer using an optical fiber. Because O_3, a powerful oxidizer, is generated by the plasma, experiments were performed focusing on the wavelength around 255 nm, which is thought to be the peak of the Hartley band (200–300 nm), which is the absorption spectrum band of ozone [3]. Measurement conditions were an accumulation time of 30 ms and an average of 20 times. Additionally, the reference incident light intensity when no voltage is applied is defined as I_C [arb. units], the transmitted light intensity at an arbitrary voltage is defined as I_O [arb. units], and the transmittance T is defined by equation (1).

$$T = \left(\frac{I_O - I_C}{I_C}\right) \times 100\ [\%] \qquad (1)$$

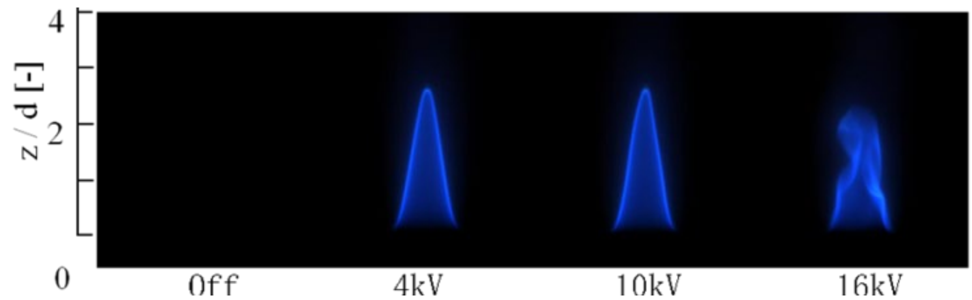
3. Results and Discussion

3.1 Flame shape comparison experiment

Figure 4 shows comparative images of premixed flames when the plasma is on and off in DBD plasma Cases A and B at an equivalence ratio of 0.95 and applied voltages of 4 kV, 10 kV, and 16 kV. At an equivalence ratio of 0.95, lean combustion occurred, the burning speed decreased, and the flame was blown out when the plasma was turned off. However, when voltages of 4 kV, 10 kV, and 16 kV were applied in both Cases A and B, although the flame surface was disturbed, the flame did not blow out and continued to burn. Furthermore, when the applied voltage was increased to 16 kV in Case A, the flame shortened and widened, and occasionally the flame shape became unstable and the flame rose up from the burner rim. In Case B, when the voltage was 16 kV, the flame front in the center vibrated up and down and burned with a sound. This is thought to be caused by the generation of an induced flow due to the DBD. Table 1 shows the range in which combustion could continue when the voltage was changed for each equivalence ratio in Cases A and B at a constant applied frequency of 4 kHz (in the table, o indicates continued combustion, and - indicates blow-out.) In both Cases A and B, the range in which combustion continued tended to increase with increasing voltage.



(a) Case A



(b) Case B

Fig. 4 Inner flame form (Q = 3.31 L/min, f = 4 kHz, φ = 0.95)

Table 1 Continuation of combustion (Q = 3.31 L/min, f = 4 kHz)

Case A

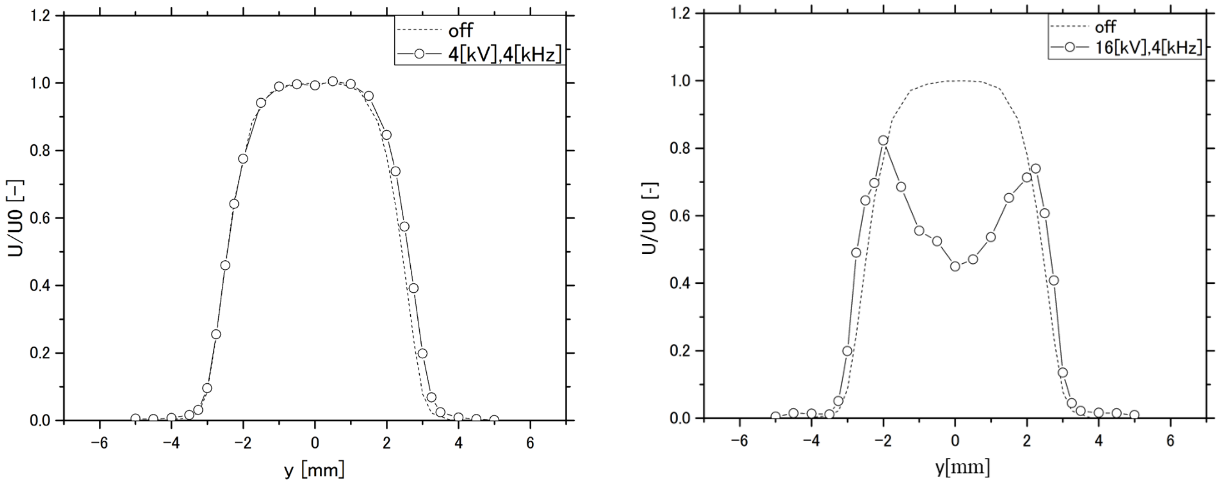
φ \ V	Off	4kV	10kV	16kV
1.00	○	○	○	○
0.95	-	○	○	○
0.90	-	-	○	○
0.85	-	-	-	-
0.80	-	-	-	-
0.75	-	-	-	-

Case B

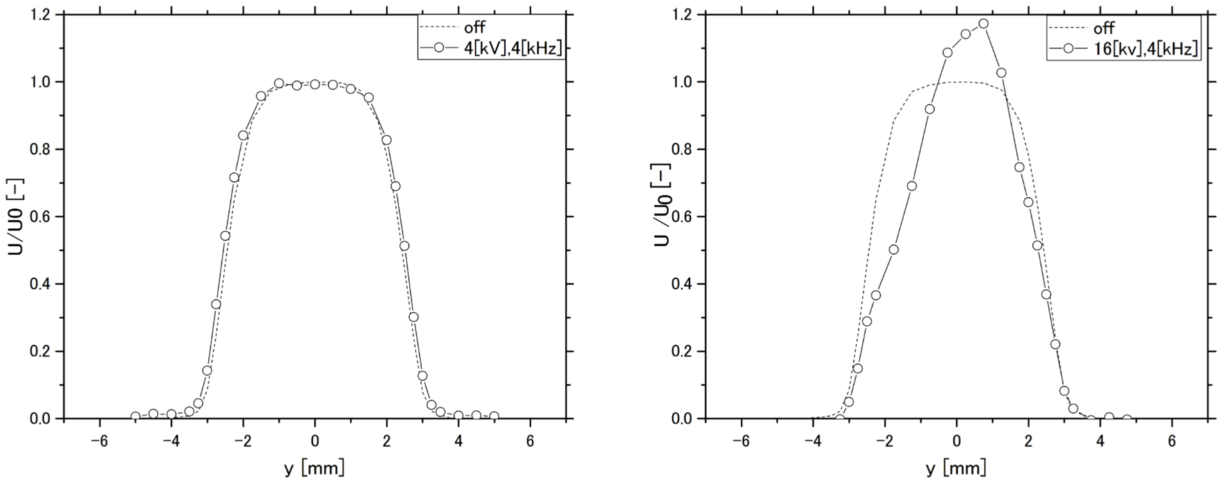
φ \ V	Off	4kV	10kV	16kV
1.00	○	○	○	○
0.95	-	○	○	○
0.90	-	○	○	○
0.85	-	-	○	○
0.80	-	-	○	-
0.75	-	-	-	-

3.2 Velocity distribution measurement using a hotwire anemometer

To investigate the effect of the induced flow generated by the DBD-PA, velocity distribution measurements were performed using a hotwire anemometer. The ejected gas was air, and to make the phenomenon inside the pipe the same, the Reynolds number Re = 870, which corresponds to an equivalence ratio φ = 1.00, was used. Figure 5 shows the average flow velocity distribution near the outlet 1 mm from the nozzle for Cases A and B. At an applied voltage of 4 kV, the flow velocity distribution was the same as when the voltage was off, indicating that the DBD-PA has almost no effect on the average flow velocity distribution. In contrast, at an applied voltage of 16 kV, a large change in the average flow velocity was observed when the plasma was off versus when the plasma was on in both Cases A and B. In Case A, the DBD-PA generated an induced flow in the same direction as the main stream, which is thought to have increased the flow velocity near the boundary layer and reduced the velocity at the center. This is thought to have shortened the flame length [Figure 4(a)]. In Case B, the DBD-PA generated an induced flow in the direction opposite to the main stream, which is thought to have slowed down the flow velocity near the boundary layer and increased the flow velocity at the center of the nozzle. This in turn is thought to have allowed the wall to suppress the blow-off of the flame shape, which led to significant turbulence in the flame shape [Figure 4(b)].



(a) Case A



(b) Case B

Fig. 5 Flow velocity distribution (air: Re = 870, z = 1 mm)

3.3 Spectroscopic measurements using spontaneous emission method

A spectroscopic experiment was conducted to investigate whether the number and amounts of chemically active species increased. Figure 6 shows the overall wavelengths of the plasma spontaneous emission results when the applied voltage was 4 kV, 10 kV, and 16 kV in Case B. It can be confirmed that various chemically active species, including OH and CH radicals, were generated by applying plasma. Figures 7 and 8 show the wavelengths thought to be CH radicals extracted from the plasma spontaneous emission and the flame spontaneous emission results, respectively. The plasma spontaneous emission results showed that no CH radicals were present from voltage off to 6 kV, but their production increased when 8 kV, 10 kV, 12 kV, 14 kV, and 16 kV were applied (Figure 7). Similarly, the flame spontaneous emission results showed an increase at 12 kV, 14 kV, and 16 kV, so it is thought that the continuation of combustion at 16 kV suppressed blow-off due to the combustion promotion effect caused by the increase in chemically active species (Figure 8). In addition, at 10 kV, the plasma spontaneous emission results showed an increase in chemically active species, but the flame spontaneous emission results showed no increase, resulting in a difference. This is thought to be because the chemically active species generated by the plasma are very unstable and react with other species before reaching the flame surface, so they are unable to affect the flame surface.

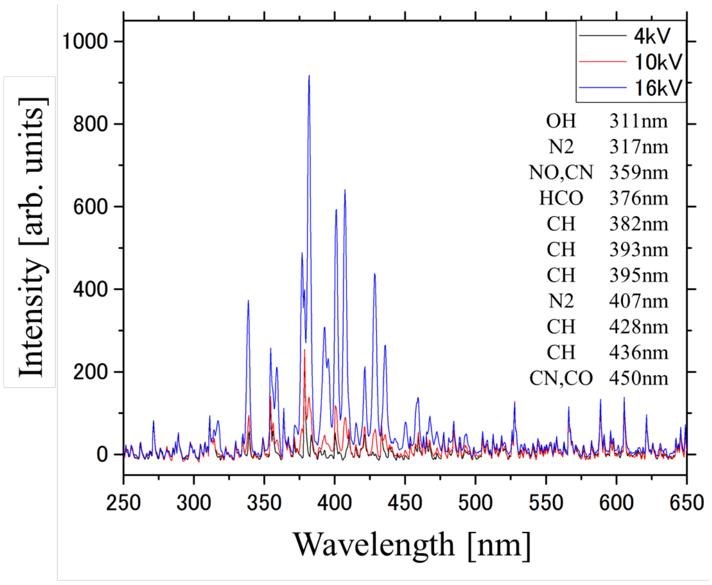


Fig. 6 Emission spectra for Case B (Q = 3.31 L/min, f = 4 kHz, φ = 1.10)

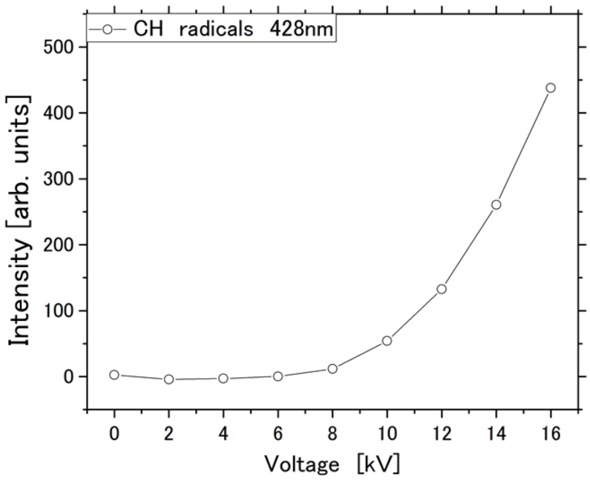


Fig. 7 CH emissions versus voltage at the plasma for Case B (Q = 3.31 L/min, f = 4 kHz, φ = 1.10) [4]

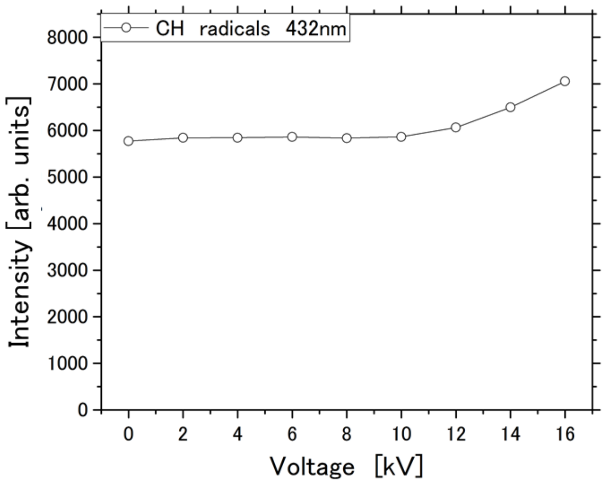


Fig. 8 CH emissions versus voltage at the flame zone for Case B (Q = 3.31 L/min, f = 4 kHz, φ = 1.10) [4]

3.4 Absorption spectroscopy and ozone concentration measurement

Figure 9 shows the transmittance T over the entire wavelength range when voltages of 4 kV, 10 kV, and 16 kV are applied to air. From these results, it is clear that ozone is generated by plasma, and an absorption wavelength band that is thought to be the Hartley band (200–300 nm), which is the absorption band of ozone, is observed. It is believed that plasma has the effect of dissociating fuel and oxidizers, which promotes combustion. Figure 10 shows the ozone concentration results when a voltage was applied from 0 kV to 16 kV in increments of 2 kV. Ozone was not generated from 2 kV to 6 kV, but was generated from 8 kV to 16 kV. At the maximum, 55 ppm was generated when only air was flowing, and 1.9 ppm was generated when propane was included at an equivalence ratio of 0.80. It is thought that this is because the ozone generated by the inclusion of propane was consumed by reacting with propane to generate new intermediate products, resulting in a decrease in the ozone concentration. This result is also very similar to the tendency of chemically active species increasing from 8 kV to 16 kV in the plasma spontaneous emission spectroscopy measurements.

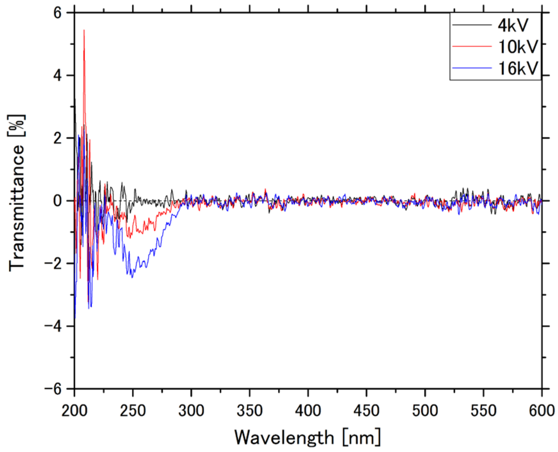


Fig. 9 Absorption spectra in air
(Q = 3.31 L/min, f = 4 kHz, no combustion)

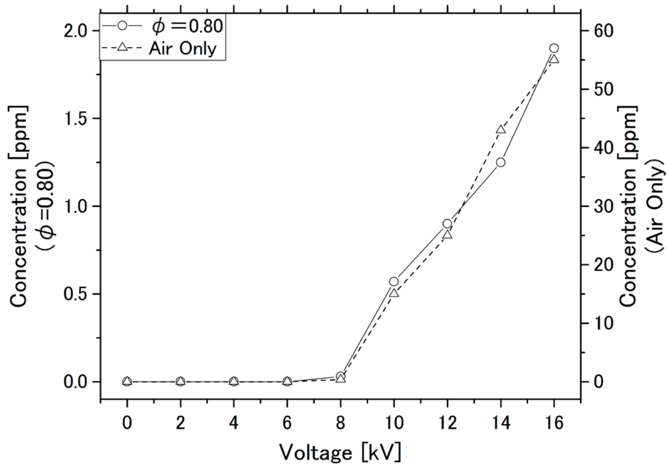


Fig. 10 Ozone concentration versus voltage for Case B
(Q = 3.31 L/min, f = 4 kHz, no combustion)

5. Conclusions

We applied a coaxial DBD-PA to a combustion burner and obtained the following findings:
1) When the DBD-PA was used at an equivalence ratio of 0.95 and voltages of 4 kV, 10 kV, and 16 kV were applied, it was possible to suppress the blow-out of a lean flame.
2) By suppressing the flow velocity near the boundary layer in Case B, it was possible to continue combustion even at an equivalence ratio of 0.80.
3) From the plasma spontaneous emission spectroscopy and flame spontaneous emission spectroscopy results, we were able to confirm an increase in chemically active species at applied voltages of 12 kV to 16 kV.
4) The ozone concentration measurements showed that ozone was generated at 8 kV to 16 kV, with 1.9 ppm generated at an equivalence ratio of 0.80 and applied voltage of 16 kV.
5) In the absorption spectroscopy experiment, when a voltage of 16 kV was applied to air, an absorption wavelength band thought to be the Hartley band, which is the absorption band of ozone, was observed.

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References

[1] Sasaki K., Uesugi Y., Ohno N., and Osaka Y., "Merging Plasma Science into Combustion Science (Plasma-Assisted Combustion)", *J. Combustion Society of Japan* (in Japanese), Vol. 51, No. 158 (2009), pp. 259-267.

[2] Takahashi E. and Asakawa D., "Fundamentals of Dielectric Barrier Discharge and Application to Combustion Control", *J. Combustion Society of Japan* (in Japanese), Vol. 64, No. 209 (2022), pp. 265-272.

[3] Okabe H., "*Photochemistry of Small Molecules*", John Wiley & Sons Inc. (1978), p. 239.

[4] Tomita K., Kanai S., Tsuchida H., Akimoto M., Kimura M., "Combustion Characteristics of Premixing Burner using Coaxial DBD Plasma Actuator", *Proc. of the 6th Symposium on Fluid Structure-Sound Interactions and Control, Busan*, South Korea, Springer, (Publication schedule 2024)