Influence of Induced Flow on Premixed Combustion Flames using Coaxial DBD Plasma Actuator

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Abstract

A DBD plasma actuator (DBD-PA) was applied to control the flame by premixed combustion. By using a coaxial DBD-PA with a premixed flame of propane and air, combustion can be continued even at low equivalence ratios that would otherwise cause blowout. The cause may be induced flow generated by DBD-PA, chemically activated species, etc. We focused on the induced flow that affects the flow, visualized the flow using incense particles, and measured the average velocity distribution using LDV. The DBD-PA using a cylindrical electrode and a dielectric was disposed at the tip of a circular nozzle with an inner diameter of d = 6 mm. The results were obtained. From flow visualization, it was confirmed that the induced flow changes and the flame shape changes. From the flow velocity measurement, it was confirmed that the change in velocity distribution and turbulence intensity distribution due to the induced flow was different depending on the presence or absence of the flame.

Keyword: *DBD plasma actuator, premixed combustion, jet, flame visualization*

1. Introduction

Many jet diffusion control methods that control the generation and growth processes of vortex rings have been proposed, and the instability of the flow is disturbed by the sound wave [1], MEMS micro-flaps [2], etc. It has been reported that the vortex ring can be amplified to increase the diffusion mixing in the initial region of the jet. In recent years, DBD-PA has attracted attention as a fluid control device, and research on wall boundary layer control has been actively conducted [3-5]. While there are few examples of application to jet control, the principal investigator is concerned with the shape and arrangement of electrodes and dielectrics, the frequency and voltage to be applied, and the jet diffusion characteristics when DBD-PA is applied to the jet from 2009. The effect of jet diffusion was studied experimentally [6-8]. On the other hand, research on ignition / combustion support technology using non-equilibrium plasma is underway, and it is expected to be applied to gasoline engine ignition for automobiles [9] and combustion stability during low-load operation of micro gas turbines. In the burner flame, which is the basic combustion mode, the velocity distribution just before the flame surface and the state of the flame base are largely related to the stability, deformation, and blow-off of the flame [10]. When DBD-PA is applied to a burner flame, in order to understand its characteristics, the structure of the flow immediately after jetting from the nozzle is considered, and a process that promotes combustion by increasing the active chemical species by the plasma is considered. It is important to understand.

We developed and manufactured a coaxial DBD-PA in which an electrode was installed on a combustion burner nozzle made of dielectric. By applying the coaxial DBD-PA to the propane and air premixed flame, it was possible to continue combustion even at a low equivalent ratio where the flame would blow off. The factors include the induced flow generated by DBD plasma, chemically active species, and the influence of electric field. In this research, we focused on the induced flow that affects the flow, and measured the flow velocity experiment using incense particles and the average velocity distribution and turbulence intensity distribution using LDV. The purpose of this study is to investigate the influence of velocity fluctuations caused by induced flow, which is one of the factors of continued combustion.

2. Experimental Apparatus

Figure 1 shows the operation of DBD-PA. DBD plasma is generated on the nozzle wall by applying AC high voltage to the electrode. As a result, an induced flow is generated on the inner surface of the nozzle. When DBD plasma is generated, an external force acts in the direction from the anode electrode to the ground electrode, and an induced flow is generated. This changes the velocity of the premixed gas passing through the nozzle and manipulates the flame. Case A is the case where the induced flow is generated in the direction along the main flow by the upper electrode and the center electrode, and Case B is the case where the induced flow is generated in the direction opposite to the main flow by the lower electrode and the central electrode. Case A and Case B are switched by circuit switching. Figure 2 shows a cross-section with a coaxial DBD-PA attached to the tip of the converging nozzle. Machinable ceramics were used for the dielectric in consideration of insulation and heat resistance. The anode and ground electrodes were made of phosphor bronze plated with gold in consideration of corrosion resistance. The inner diameter of the nozzle outlet is d = 6mm, the thickness of the dielectric between the electrodes is 1mm, and the thickness of the anode and ground electrodes is 0.5mm. AC voltage from a function generator (NF: WF1974) is amplified by 2000 times at the peak-to-peak ($V_{p\text{-}p}$) using an amplifier (Matsusada Precision Co., Ltd .: HAP-20B20), and then applied to the electrodes. DBD plasma is emitted. All voltages are alternating rectangular voltages.
The following experiment was conducted. (1) Flame shape comparison using a high-speed camera (Photron: FASTCAM Mini AX100). (2) Flow visualization using incense particles to confirm the effect of induced flow. (3) Flow velocity measurement using LDV (DANTEC DYNAMICS, Flow Explorer) to confirm the influence of induced flow with specific numerical values. Figure 3 shows the experimental setup.
[Flame shape comparison using a high-speed camera] Air is supplied from the compressor, and industrial pure propane is supplied from the gas cylinder. Using a digital mass flow controller (Azbil Corporation: MQV0005, MQV0002), create a premixed gas mixture in the chamber and supply it to the nozzle in the range of Q = 3.31 ± 0.01L / min (≒ 1.95m / s), and ignite at the nozzle outlet. Mixing was performed so that the equivalence ratio changed from φ = 0.80 to 0.95 by 0.05. After ignition, an AC rectangular voltage was applied to DBD-PA to generate DBD plasma, and the situation at that time was observed and recorded. Table 1 shows the experimental conditions for flame shape photography using a high-speed camera.
[Flow visualization using incense particles]

In the visualization experiment, the case where only air was ejected and the case where there was a flame were carried out. A smoke tank was attached to the tip of a flow controller that supplies air, mixed with incense particles, and irradiated with a laser sheet light and photographed using a high-speed camera. In the case of air only, the experiment was carried out at the same Reynolds number Re = 870 (Q = 3.48 ± 0.01 L /min ($U_{ave} \approx 2.08$ m/s)) as the equivalent ratio φ = 1.00. In the case of the inside of the flame, the experiment was conducted with an equivalence ratio of φ =1.15 and Q = 3.31 ± 0.01 L/min (≒ 1.95 m/s). The experiment was carried out with the applied frequency and applied voltage being the same as those for flame shape photography, and the photography speed was 13600 fps.
[Flow velocity measurement using LDV]

As in the flow visualization experiment, incense particles were mixed as tracer particles. The flow velocity was measured under two conditions: when only air was blown out and when measured inside the flame. The ejection flow rate and applied frequency were the same as those for flame imaging and flow visualization, and the applied voltage was only $V_{p\text{-}p}$ = 14 kV.

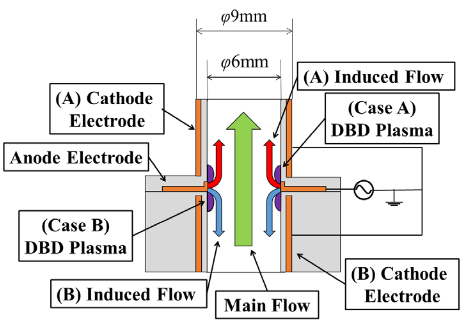

Fig. 1 Flow control by induced flow due to DBD-PA

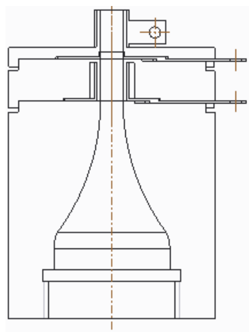

Fig. 2 Cross-section with a coaxial DBD-PA on the converging nozzle

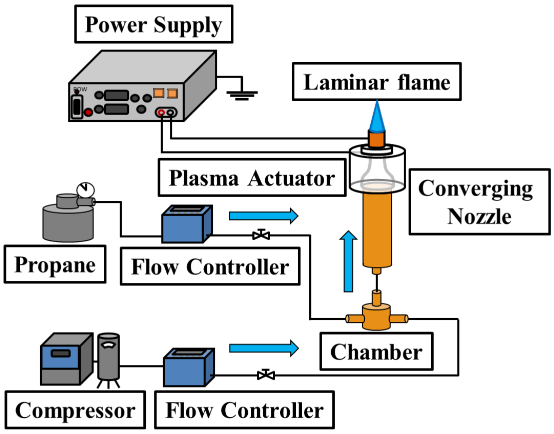

Fig. 3 Experimental apparatus on the converging nozzle

Table 1 Experimental condition

Flow rate Q	3.31 [L/min] (1.95 [m/sec])
Applied voltage $V_{p\text{-}p}$	4, 10, 14 [kV]
Applied frequency f	4 [kHz]
Using gas	Propane, Air (Premixed gas)
Equivalent ratio φ	0.80 ~ 0.95 [-]
Shooting speed	125 [fps]

4. Experimental Results and Discussion

4.1 Flame shape comparison

Equivalent ratio φ = 0.95, applied frequency f = 4kHz, applied voltage $V_{p\text{-}p}$ = 4 kV, 10 kV, 14 kV, and comparison image of premixed flame with equivalent ratio φ = 1.05 and voltage OFF for comparison, it is shown in Fig. 4. In comparison with the OFF state, no change in the flame shape could be confirmed at the applied voltage $V_{p\text{-}p}$ = 4 kV for both Case A and Case B, but a slight change was observed at the applied voltage $V_{p\text{-}p}$ = 10 kV. At $V_{p\text{-}p}$ = 14 kV, a large flame shape change was confirmed. Focusing on the large change in applied voltage $V_{p\text{-}p}$ = 14 kV, in Case A, the flame length was shortened, and the rolling of the flame was not seen much. In Case B, it was confirmed that the flame was violently disturbed from side to side. These changes in the flame shape are thought to be due to the change in the premixed gas flow entering the flame surface due to the induced flow by DBS-PA. Tables 2 show the results of confirming the continuation of combustion when the equivalence ratio is changed. "O" indicates that the combustion was continued, and "X" indicates that the combustion did not continue and was blown out. From Tables 2, in both Case A and Case B, the applied voltage $V_{p\text{-}p}$ = 4 kV up to an equivalent ratio φ = 0.95, and the applied voltage $V_{p\text{-}p}$ = 10 kV up to an equivalent ratio φ = 0.85, at $V_{p\text{-}p}$ = 14 kV, it was possible to continue combustion until the equivalence ratio φ = 0.90. Compared with the applied voltage $V_{p\text{-}p}$ = 4 kV, the applied voltage $V_{p\text{-}p}$ = 10 kV and 14 kV could continue to burn at a lower equivalent ratio because the induced flow strongly generated as the applied voltage increased. It is thought that the change in the flow of the air-fuel mixture and the change in the flame shape may be the continuation factor of combustion. In addition, the applied voltage $V_{p\text{-}p}$ = 10 kV can continue combustion at a lower equivalent ratio than the applied voltage $V_{p\text{-}p}$ = 14 kV. This is thought to be due to the fact that the flame is more fluctuating at the applied voltage $V_{p\text{-}p}$ = 14 kV, and the surrounding gas is entrained, resulting in a lean state.

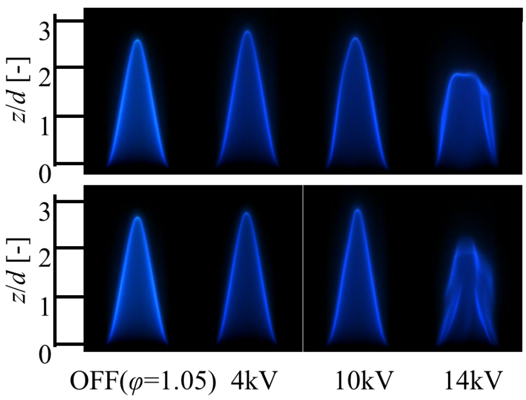

Fig. 4 Flame comparison
Condition: Q = 3.31 L/min, f = 4 kHz, φ = 0.95, 125 fps, Top: Case A, Induced flow is in the direction along the main flow, Bottom: Case B, Induced flow is in the direction opposite the main flow

Table 2 Confirm continuation of combustion

[Case A]

	OFF	4kV	10kV	14kV
0.95	×	○	○	○
0.90	-	×	○	○
0.85	-	-	○	×
0.80	-	-	×	-

[Case B]

	OFF	4kV	10kV	14kV
0.95	×	○	○	○
0.90	-	×	○	○
0.85	-	-	○	×
0.80	-	-	×	-

4.2 Flow visualization using incense particles

It was thought that by generating the induced flow, the flow of the premixed gas was changed and influenced the continuation of combustion. In order to confirm the change, we conducted a flow visualization experiment using incense particles. Figure 5 and 6 show the flow visualization images when the plasma is generated and the voltage is OFF at the applied frequency f = 4 kHz and the applied voltages $V_{p\text{-}p}$ = 4 kV, 10 kV, and 14 kV. Fig. 5 (Top) shows the visualization results inside the flame in Case A, Fig. 5 (Bottom) shows the visualization results inside the flame in Case B, and Fig. 6 (Top) shows the visualization results of the jet flow in Case A. Fig. 6 (Bottom) shows the visualization results of the jet in Case B. All vertical axes are the same as in the flame shape comparison experiment (z/d, z: jet direction, d: nozzle exit diameter).

From Fig. 5 (Top) and (Bottom), in both Case A and Case B, no change was observed in the internal state of the flame when applied voltage $V_{p\text{-}p}$ = 4 kV compared to when the voltage was not applied. At the applied voltage $V_{p\text{-}p}$ = 10 kV, it was confirmed that the flow of the internal premixed gas changed with the change of the flame surface. At the applied voltage $V_{p\text{-}p}$ = 14 kV, it was confirmed that the internal premixed gas changed along with the change of the flame shape. From this, it is considered that the change in the flame shape confirmed in Fig. 4 was caused by the change in the velocity of the premixed gas entering the flame surface due to the induced flow.

Next, in order to confirm the change of the premixed gas, a visualization experiment was performed on the jet. As can be seen from Figs. 6 (Top) and (Bottom), in both Case A and Case B, the applied voltage $V_{p\text{-}p}$ = 4 kV is similar to that in the flame, as compared to the OFF state when no voltage was applied. There was no change in the appearance. At applied voltage $V_{p\text{-}p}$ = 10kV, a slight change was confirmed after z/d = 1.0. At the applied voltage $V_{p\text{-}p}$ = 14 kV, a vortex was generated, and it was confirmed that the turbulence was larger than when the applied voltage $V_{p\text{-}p}$ = 10 kV.

Also, pay attention when the change is large: applied voltage $V_{p\text{-}p}$ = 14 kV. In Case A, the flow begins to be turbulent around z/d = 1.0, and vortices are generated and diffused. In Case B, the flow is turbulent immediately after the nozzle exit, and diffusion is earlier than in Case A. It was confirmed. This is thought to be due to the difference in the direction of the induced flow. In Case A, it occurred in the direction along the mainstream, so the velocity near the boundary layer increased, and the velocity difference from the surrounding gas increased compared to when it was turned off. In Case B, it occurs in the direction opposite to the main flow, so the velocity near the wall surface decreases in the nozzle, the nozzle center velocity increases due to the constant flow rate, and the velocity difference in the jet is larger than when OFF. It seems that turbulence was promoted.

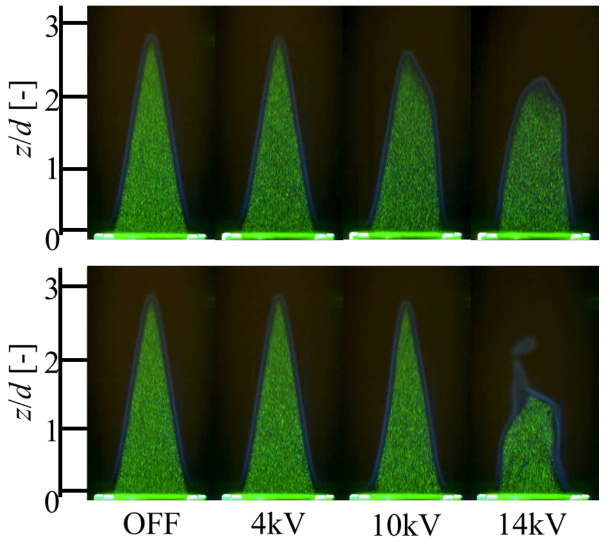

Fig. 5 Comparison of flame visualization Condition: Q = 3.31, 3.48 L/min, f = 4 kHz, φ = 1.15, 13600 fps, Top: Case A, Flame interior, Induced flow is in the direction along the main flow, Bottom: Case B, (Flame interior, Induced flow is in the direction opposite the main flow

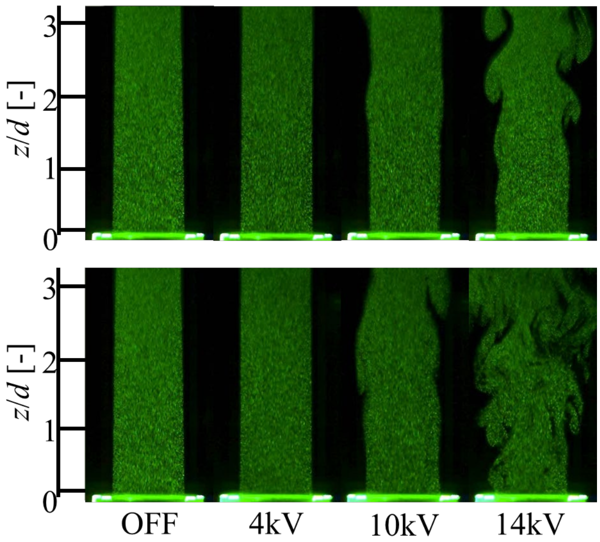

Fig. 6 Comparison of flow visualization Condition: Q = 3.31, 3.48 L/min, f = 4 kHz, φ = 1.15, 13600 fps, Top: Case A, Jet, Induced flow is in the direction along the main flow, Bottom: Case B, Jet, Induced flow is in the direction opposite the main flow

4.3 Flow velocity measurement using LDV

In order to confirm the change of the flow by the induced flow confirmed by the flow visualization experiment, the flow velocity was measured for the inside of the flame and the jet using LDV. In order to compare the two, the measurement position was on the *z*-axis (on the nozzle center axis). The measured data are shown in Fig. 7 and 8 as average velocity distribution and turbulence intensity distribution. Fig. 7 shows the measurement result in the flame, and Fig. 8 shows the measurement result in the jet. The left vertical axis is the dimensionless number obtained by dividing the measured average velocity U by the nozzle outlet center average velocity U_0, the right vertical axis is the dimensionless number obtained by dividing the measured turbulence u' by the nozzle outlet center average velocity U_0, and the horizontal axis is a dimensionless number obtained by dividing the measurement position z by the nozzle diameter d. Each plot shows the average velocity for the white ones, and the turbulence intensity for the ones filled. Black is OFF when no voltage is applied, red is Case A applied voltage $V_{p\text{-}p}$ = 14 kV, blue is Case B The applied voltage $V_{p\text{-}p}$ = 14 kV.

From Fig. 7 and 8, focusing on the average velocity distribution, it can be confirmed that Case A is decelerating overall from OFF and Case B is generally accelerating. This is because the velocity near the wall is accelerated in Case A and decelerated in Case B due to the induced flow. From the relationship of constant flow rate, the nozzle center velocity is decelerated in Case A and accelerated in Case B.

However, the results inside the flame (Fig. 7) confirmed that Case A and Case B were accelerating after z/d = 1.5. This is considered to be the result of the presence of the flame surface, and it is thought that the contraction occurred due to the fluctuation of the flame surface by the induced flow, and it was accelerated. Next, focusing on the turbulence intensity distribution, the results of the jet (Fig. 8) show a certain degree of turbulence intensity in both Case A and Case B, and the value increases as z/d increases. It was confirmed that it increased. As confirmed by visualization, this is thought to be due to the fact that the jet diffuses as it moves downstream. However, the result inside the flame (Fig. 7) confirms that this is not the case. Inside the flame (Fig. 7), the increase in turbulence intensity with increasing z/d cannot be confirmed in Case A. But Case B showed the largest value immediately around the nozzle outlet, and after that, it was confirmed that the value decreased as z/d increased. The difference between these changes is considered to be that the turbulence intensity was suppressed because the internal premix gas temperature increased and the viscosity increased due to the presence of the flame surface. Therefore, in Case A, the turbulence intensity did not increase with increasing z/d, and in Case B, the turbulence intensity decreased with increasing z/d. In Case B, the turbulence intensity immediately after the nozzle exit is large. This can be considered from the visualized images observed in Fig. 4 (Bottom) and Fig. 5 (Bottom). The applied voltage $V_{p\text{-}p}$ = 14 kV is considered to be because the speed of the premixed gas entering the flame base changes drastically due to the induced flow, and unlike the case of Case A, it appears to be an irregular expansion and contraction of the flame.

From the above, it was confirmed that the velocity distribution and the turbulence intensity distribution were changed by the induced flow. Due to the presence of the flame surface, it was confirmed that the state of the change was different from that of the jet only. In addition, the following factors are considered to be the reasons why the lean flame continued to burn at the applied voltage $V_{p\text{-}p}$ = 14 kV for Case A and Case B. This is thought to be because the velocity distribution and turbulence intensity distribution of the premixed gas changed due to the induced flow, the flame shape was disturbed, and the combustion velocity changed to balance the premixed gas supply rate.

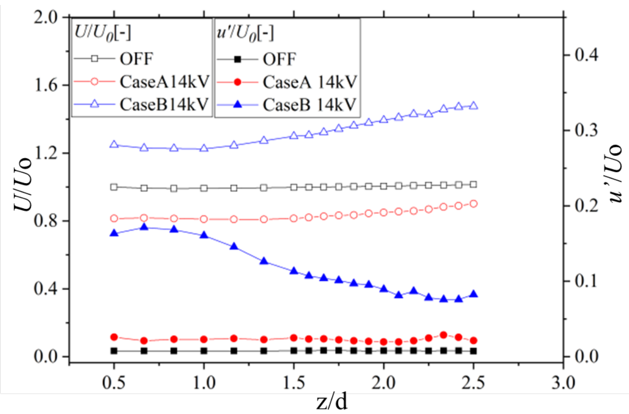

Fig. 7 Flame interior velocity and turbulence on the center axis of nozzle

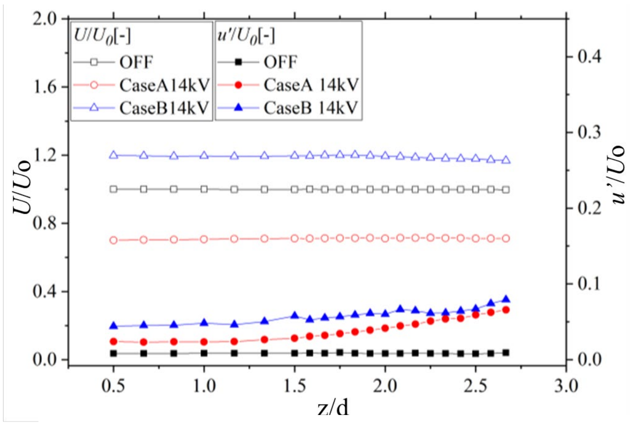

Fig. 8 Jet velocity and turbulence on the center axis of nozzle

5. Conclusion

As a result of using the coaxial DBD-PA for laminar premixed flame, the following knowledge was obtained.
(1) When the coaxial DBD-PA was driven with an applied voltage of $V_{p\text{-}p}$ = 4 kV, 10 kV, and 14 kV at an equivalence ratio of 0.95, the blowout of the dilute flame could be suppressed. Combustion can be continued up to an equivalence ratio of 0.85 at an applied voltage $V_{p\text{-}p}$ = 10 kV and to an equivalent ratio of 0.90 at an applied voltage $V_{p\text{-}p}$ = 14 kV.
(2) From the flow visualization experiment, it was confirmed that the applied flow changed the velocity of the premixed gas at the applied voltage $V_{p\text{-}p}$ = 10 kV and 14 kV, and the flame shape changed due to the change in the velocity.
(3) From the results of the flow velocity measurement experiment, it was confirmed that there was a difference in the change in the velocity distribution and turbulence intensity distribution due to the induced flow depending on the presence or absence of flame at the applied voltage $V_{p\text{-}p}$ = 14 kV. In addition, the change in the flame shape changed the combustion velocity, which was thought to have suppressed the blow-off.

6. Acknowledgments

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