Edge flame propagation via parallel electric fields in nonpremixed coflow jets

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Abstract

Recent investigations suggested that the primary influence of an electric field on a flame is flow modification caused by ionic wind, and that negative ions produced by the electron impact attachment should play a key role in the bi-directional ionic wind. In order to prove this hypothesis in electric fields parallel to the propagating flames, we designed a coflow experiment with laminar lifted flames in vertical electric fields produced by a nozzle and ground electrode installed over the flame. We found that applying DC and AC increased the flame displacement speed, and decreased the unburned velocity even to negative velocity. Velocity measurements revealed the influence of the electric body force on the flow volume, indicating the importance of the electron impact attachment when the nozzle was charged with positive voltage. The flame propagation speeds were estimated by subtracting the unburned velocity from the displacement speed, and were well correlated with those of stationary lifted flames without an applied electric field as a function of flame curvature. This supported our hypothesis that the effect of the electric field is reflected in the flow modification, and that the flame is affected by the modified flow. It also suggested that the propagation direction of premixed or nonpremixed edge flames can be manipulated by coupling the appropriate electric fields.

Keywords: electric field, lifted flame, edge flame, propagation, ionic wind

1. Introduction

The primary impact of electric fields on flames is the separation of ions and electrons from the origin (reaction zone), letting them migrate toward electrodes—positive ions to a cathode, and electrons and negative ions to an anode. The separation of these charged species imposes electrical charges on the flow volume, ending neutrality in the flame zone such that the electric body force on the flow volume creates a bulk flow motion, i.e., ionic wind, blowing from the flame toward both electrodes [1–3].

Here, based on two important features of flames—i) negative charges are mostly carried by electrons due to the small amounts of negative ions and neutrality, and ii) the electrons' mobility (μ_e) is three orders of magnitude greater than that of the ions (μ_{ion})—the electric field results in a unique and intriguing flow modification. Because of the significantly higher mobility of electrons than ions, the migration of electrons to an anode is much faster than that of positive ions to a cathode, such that the charge density in the region between the flame and the anode is significantly smaller than the corresponding region between the flame and the cathode, since electron density $\sim (\mu_{ion}/\mu_e) \times$ positive ion density. This indicates an asymmetric field intensity, which is caused by the significantly different charge densities. Therefore, the response of the ion current in a flame to an electric field is significantly different depending on polarity, particularly when the flame is closer to one of the electrodes [4,5,6].

In addition to the response of the ion current, the charge density in the flow volume also causes electric body force. The electric body force caused by electrons is negligibly small ($\sim O(10^{-3})$) compared to that caused by positive ions. Therefore, a unidirectional ionic wind mostly caused by the slower moving positive ions should blow from the flame to the cathode. However, our previous studies [2,3,7,8] found a bi-directional ionic wind blowing from the flame to both the anode and the cathode, which indicates that negative ions traveling to the anodes have an equally important role. Since the amount of flame-generated negative ions is negligibly small [9], the electron attachment to oxygen and water molecules during the electron migration process due to their high electronegativities may be

responsible for ionic wind blowing toward an anode [3]. A study of premixed and nonpremixed jet flames under various direct current (DC) and alternating current (AC) conditions recently visualized the three-dimensional nature of ionic wind [3]. Note that Weinberg and colleagues knew the nature of ionic wind [1], however, the visual impact of drastically tilted flame toward a cathode [10] somewhat misled researchers to have a false impression that ionic wind blows from an anode to a cathode—unidirectional.

Tran and Cha [7,8] recently reported that the displacement speeds of nonpremixed edge flames were reduced when both DC and AC electric fields were applied orthogonal to the propagating direction of the edge flames. However, no significant effects of the electric fields on the flame propagation speeds, i.e., on the overall reaction, were found when the displacement speeds were corrected into the flame propagation speeds with the unburned flow velocities. This indicates that the effect of the electric field on the flame chemistry is negligible. Nevertheless, the flame is directly affected by the flow modification caused by ionic wind. This exhibits the importance of directional coupling between the flame propagation and the electric field. The reduced displacement speeds in the orthogonal electric fields implies that the flame displacement speeds should be augmented when the electric field lines are parallel to the direction of flame propagation.

Therefore, previous investigations of increased flame propagation speeds in laminar nonpremixed lifted jet flames [11] should be revisited to clarify the true effect of electric fields. When a fuel nozzle located far below a ground electrode is energized with high voltages, nonpremixed lifted flames in the inter-electrodes region are subjected to the vertically established electric fields parallel to the propagating direction of the flame. In this parallel electric-field configuration, we hypothesize that a reduction in the unburned velocity near the flame base is caused by ionic wind blowing from the flame toward the nozzle for various types of high voltages [2,3,7,8]. Because of the stabilization mechanism of a lifted flame, which is the balance between the propagation speed of a flame edge and the upstream unburned velocity ahead of the edge [12], an initially stationary lifted flame will

propagate toward the nozzle due to the reduced upstream velocity with applied electric fields. Thus, the vertical displacement speed (u_d) of that propagating lifted flame can be expressed as a vector sum of a propagation speed of flame edge (u_{edge}) and the vertical component of unburned velocity in front of the edge (u_u): $u_d = u_{\text{edge}} + u_u$.

In the present study, we confirmed experimentally the hypothesis that the augmented flame displacement speeds under electric fields parallel to the propagating direction are a result of the flow modification caused by ionic wind in nonpremixed lifted jet flames. Both DC and AC were tested with different polarities and frequencies. Flow visualization and velocity field measurements reflected drastic modification of the cold flow. Here, we discuss the propagation speed of a flame edge in conjunction with a flame curvature (mixture fraction gradient) in detail, and highlight the importance of the electron impact attachment to ionic wind generation by comparing different polarities in DC.

2. Experiment

The experimental setup consisted of a coflow burner, a flow control and particle seeding system, a high voltage system, and visualization setups. Figure 1 shows a schematic diagram of the coflow burner and the configuration of the electrodes. The central nozzle of the coflow burner was a 35cm long stainless-steel tube, with inner and outer diameters of 4 and 6 mm, respectively, to ensure a fully developed velocity profile at the nozzle exit. A layer of glass beads filled in the coflow section (inner diameter = 9.4cm), and a ceramic honeycomb (15mm thick) was installed near the nozzle exit to obtain a uniform velocity profile. Air was supplied to the coflow section and the velocity (u_{co}) was fixed at 5cm/s. An 18cm long cylindrical confinement (inner diameter = 9.4cm, acetal resin) with four optically accessible quartz windows was installed on the coflow burner. Propane (99.5% purity) was used as the fuel to provide a comparison with the previous study [11] and, to obtain laminar lifted flames for the given nozzle diameter, was diluted with nitrogen maintaining an initial fuel mole fraction (X_F) at 0.1 in all cases. All gases were controlled using mass flow controllers (Brooks Instrument, 0260 Series),

and the nozzle exit mean velocity (u_o) was set at 35, 50 and 65 cm/s, respectively.

Fig. 1. Schematic of the coflow burner and electrical configuration.

A high voltage was applied to the nozzle using a power supply (Trek, 40/15-H-CE), while the grounded metallic-mesh electrode (diameter 12.4cm) was installed on top of the confinement at a distance of 18cm from the nozzle (Fig. 1). In this way, we established a vertical electric field parallel to the propagating direction of the lifted flames. The voltage waveform was controlled with a function generator (NF, WF 1974) connected to the power supply, which produced a sinusoidal AC with various frequencies (f_{AC}), and both positive and negative DC. The magnitude of the applied voltage was up to 10kV in root mean square (rms) values for AC, and the applied AC frequency ranged from 1 to 1000Hz. The applied voltage (V_{AC} for AC and V_{DC} for DC) and f_{AC} were monitored by an oscilloscope (Tektronix, TPS2000B) using a 1000:1 high-voltage probe (Tektronix, P6015A).

High-speed imaging with a high-speed camera (Photron, FASTCAM MC2.1) was adopted to analyze the dynamic motion and flow characteristics of the flame. The flame displacement speed (u_d) was obtained via high-speed imaging. We conducted flow visualization and particle image velocimetry

(PIV) by supplying oil-mist as seeding particles (Smoke Oil 180) to the flow and illuminating these with a continuous-wave diode laser (Coherent, Genesis 532-2000 S OPSL). The framing rate of the high-speed images was 1000Hz, and two consecutive images were used to quantify the flow field. The measured unburned velocity (u_u) ahead of a flame edge and the displacement speed were used to deduce the flame propagation speed (u_{edge}) as $u_{\text{edge}} = u_d - u_u$. Note that, in our previous studies [2, 3, 7, 8], both the oil-mist and TiO_2 particles were found to be minimally influenced by electric fields, exhibiting no quantitative dependence of PIV analysis on them. In addition, the effect of the oil-mist on flames was found to be minimal in the present study, showing negligible difference in the flame displacement speed between the cases with and without the oil-mist. The choice of the oil-mist was to avoid clogging up the packed beads layer caused by solid particles.

A planar laser-induced fluorescence (PLIF) setup, consisting of a Nd:YAG pulsed laser (Continuum, Powerlite DLS 9010), a tunable dye laser (Continuum, ND6000), and a frequency doubling unit (Continuum, UVT-3), was used to visualize the distribution of OH radicals. The $Q_1(6)$ transition $A^2\Sigma^+ - X^2\Pi$ (1,0) band of OH radicals at 282.96 nm was selected for the excitation. An intensified charge-coupled device (ICCD) camera (Princeton Instruments, PI-MAX2) with a UV lens and a set of optical filters (WG305 and UG11) captured the fluorescence signal. A delay generator (SRS, DG535) was used to control the time sequences for the power supply and measurement systems when necessary.

3. Results and discussion

3.1. Overall flame and flow characteristics

To investigate the previously mentioned hypothesis—electric fields parallel to the direction of flame propagation should increase the flame's displacement speed and have minimal influence on the flame's propagation speed—we established three lifted flames ($u_o = 35, 50$, and 65cm/s , respectively,

at $X_F=0.1$) and applied various voltages. We identified four distinctive flame responses to the electric fields: i) a stable lifted flame with lowered flame position (Supplementary movie, SM1); ii) extinction of the flame due to upstream instability (SM2); iii) propagation of the flame toward the nozzle exit, then bouncing back to blow out (SM3); and iv) flame fluctuation due to oscillation upstream in a low f_{AC} (SM4). In the supplementary movies, the oil-mist was added only in the coflow stream; thus, the dark columns at the center indicate fuel streams, and the edges of the dark zones near to and downstream of the flames represent an iso-thermal contour caused by the evaporation temperature of the oil (~ 500 K).

Fig. 2. Stabilized liftoff heights with $u_o = 35$ and 65 cm/s for various DC and AC conditions.

To detail the overall flame behaviors, we analyzed the flame liftoff height (H_L)—the distance between the flame base and the nozzle exit—in terms of the applied voltage for the stable lifted flames (Fig. 2), and the elapsed time after applying the voltages in the transient cases (Fig. 3). Figure 2 illustrates the variation in the flame liftoff heights at $u_o = 35$ and 65 cm/s for various applied voltages, including positive and negative DC and AC, with $f_{AC} = 1, 10, 100$, and 1000 Hz. The data are represented at $V_{DC} = \pm 1, \pm 2, \pm 4, \pm 10$ kV and $V_{AC} = 1, 2, 4, 10$ kV (rms), since a comprehensive mapping of the dynamics in the flames was not our primary objective.

When DC was applied, the stable lifted flame exhibited a decreased H_L for both polarities (also see SM1). The effect of DC polarity on the restabilized flame position seemed to be minimal, although

H_L was slightly lower with the negative voltages than with the positive ones. However, for $|V_{DC}| \geq 4\text{kV}$ at $u_o = 35\text{cm/s}$, the lifted flame propagated down to the nozzle from its original position ($H_L = 32.3\text{mm}$), and was either extinguished after bouncing back from the nozzle (SM3) with negative DC or was extinguished by the upstream instability (SM2) with positive DC. For $u_o = 65\text{cm/s}$ with the initial $H_L = 87.7\text{mm}$, however, the stable lifted flames were found at higher voltages in the range $-4\text{ kV} \leq V_{DC} \leq 10\text{ kV}$, while the flames propagated toward the nozzle showing blowout afterwards at $V_{DC} \leq -8\text{ kV}$. The local electric field intensity at the flame became weaker as H_L increased because the area of the upper electrode (circular mesh) was significantly greater than the annular area of the lower electrode (nozzle). Thus, as H_L increased, a higher applied voltage was required to maintain a similar level of local electric-field intensity at the flame.

For the AC cases, variations in H_L were negligible as long as $|V_{AC}| \leq 2\text{ kV}$ at $u_o = 35\text{cm/s}$, regardless of f_{AC} . Also, $|V_{AC}| \leq 4\text{ kV}$ showed no significant effect on H_L for all tested f_{AC} at $u_o = 65\text{cm/s}$. When $|V_{AC}| \geq 4\text{ kV}$ at $u_o = 35\text{cm/s}$, the flames propagated toward the nozzle leading to blowout for all f_{AC} . At $u_o = 65\text{cm/s}$, the flame only extinguished due to upstream instability when $f_{AC} = 1$ and 10Hz for $|V_{AC}| \geq 8\text{kV}$ (SM4), which can be partially attributed to a cold field emission of electrons and their attachment to oxygen molecules, as reported previously [13].

Fig. 3. Time history of unsteadily propagating flames with $u_o = 35$ and 65cm/s for various DC and AC conditions.

Figure 3 illustrates the temporal behaviors of the flames, tracing the positions of the flame base (leading edge) from the high-speed images at $V_{DC} = \pm 10\text{kV}$ and $V_{AC} = 10\text{kV}$. The flames propagating toward the nozzle were particularly interesting cases due to their dynamic motions. In this graph, the local slope between two adjacent data indicates the instantaneous displacement speed of the flame. Comparing the polarity of DC at $u_o = 35\text{cm/s}$, the negative applied voltages resulted in a faster propagating flame than the positive ones. This was further evidenced by the flame at $u_o = 65\text{cm/s}$: $V_{DC} = -10\text{kV}$ pulled the flame down to the nozzle in 1.5s, but $V_{DC} = 10\text{kV}$ stabilized the flame at $H_L = 59\text{mm}$ after 2.7s. These different behaviors can be understood based on the greatly different mobility of electrons and their attachment to oxygen molecules depending on the polarity, forming negative ions and affecting the flow modification. The propagating behaviors with $u_o = 35\text{cm/s}$ under $V_{AC} = 10\text{kV}$ and $f_{AC} = 100\text{Hz}$ were similar to the case with $V_{DC} = -10\text{kV}$, whereas the behavior with $u_o = 65\text{cm/s}$ showed a stable flame, indicating that the changes in behaviors were localized phenomena with no generalized relation to the type of applied voltage.

Fig. 4. Visualization and quantification of flow fields with $u_o = 35\text{cm/s}$ for $V_{DC} = \pm 10\text{kV}$ and $V_{AC} = 10\text{kV}$ at $f_{AC} = 100\text{Hz}$. The maximum and minimum velocity in the color code were chosen to drastically show flow modification due to ionic wind.

To further investigate the responses to different voltage types, the PIV results were compared at $u_o = 35\text{cm/s}$ with $V_{DC} = \pm 10\text{kV}$, $V_{AC} = 10\text{kV}$ and $f_{AC} = 100\text{Hz}$ (Fig. 4); $t = 0$ indicates the moment when the voltage was applied. Four instants, when the corresponding H_L of the foremost flame edges was 3.25, 2.50, 1.75, and 1.00mm, respectively, were selected for comparison. The slowest propagating flame was at $V_{DC} = 10\text{kV}$, and required the longest time to reach a certain point compared to other conditions.

We compared the polarity difference in DC by highlighting the local unburned velocity near the flame base. The upstream flow velocity (negative) near the flame with $V_{DC} = -10\text{kV}$ was significantly higher than that with $V_{DC} = 10\text{kV}$, and the flow volume with negative velocity (yellow–red in the color code) was also discernibly larger than that with $V_{DC} = 10\text{kV}$.

This negative velocity zone was caused by ionic wind caused by the applied electric field. When a negative voltage was applied to the nozzle, positive ions traveled downward to the nozzle. These positive ions should have been mostly H_3O^+ [9]; but the nascent ions extracted from the reaction zone also should include CHO^+ . Therefore, the ionic wind had to be generated from the flame. On the other hand, when a positive voltage was applied to the nozzle, the charge carriers extracted from the nozzle side were electrons. Because of the significantly higher mobility of electrons than of ions, the charge density near the nozzle was smaller than in the case with the negative voltage. This was supposed to result in the effect of the electric body force being insignificant, such that no flow modification occurred in the upstream region.

However, there was significant flow modification with $V_{DC} = 10\text{kV}$ (Fig. 4), which indicates the validity of the electron impact attachment with oxygen molecules to form negative ions. But, due to the finite rate of electron impact attachment, the charge density increased as the electrons moved toward the nozzle. Therefore, the negative velocity zone was smaller than in the case with $V_{DC} = -10\text{kV}$, which can be attributed the slower upstream displacement of the flame. In the case with $V_{AC} = 10\text{kV}$, the flame showed an asymmetric propagating edges (the flame edge in the right is faster than that in the left). The compression of the fuel jet encapsulated by the electric body force resulted in a collapse of the fuel jet, similar to the buckling of a solid column, as shown in Fig. 4 for both DC cases. However, the fuel jet buckling could not be captured in the AC case because the asymmetric propagating flame edges left a weak open area in the left, where the fuel jet erupted (rerouted) as shown in Fig. 4 (PIV result).

Detailed measurements of the flow fields suggested that the dynamic motion of the flame could

be explained using local flow field near the flame edges rather than global parameters, such as applied voltage and u_o . Thus, the instantaneous flame propagation characteristics will be analyzed in the following section.

3.2. Flame propagation speeds and the effect of electric fields

Appropriate measurements of the flame displacement speed and the local unburned velocity ahead of a flame edge are required to estimate the flame propagation speed ($u_{\text{edge}} = u_d - u_u$). The flame displacement speed was determined from the flame locations at a given time (Fig. 3); we note that this was the vertical displacement speed based on the foremost leading edge of the flame (see the circular point a in Fig. 5). The local unburned flow velocity was measured systematically as follows. Because the evaporation temperature of the oil was $\sim 500\text{K}$, it was unable to measure the unburned flow velocity very near the leading edge. Therefore, we had to select a location, where the measurement of the unburned velocity was made, along the boundary of the oil-mist which could be considered as the early stage of a thermal layer caused by the flame. Then, the crossing point of the vertical line from the leading edge (a) with the boundary of the oil-mist (see the circular point b in Fig. 5) determined the measurement point of the unburned flow velocity. Since we considered the vertical displacement of the flame, only vertical unburned velocity was used to estimate the vertical propagation speed of the flame edge.

Figure 5 shows a flow visualization with the lifted flame at $u_o = 65\text{cm/s}$ and $V_{\text{DC}} = 10\text{kV}$. The hydroxyl radical distribution is shown in the right half of Fig. 5, concentrated along the trailing diffusion flame. Thus, the most reactive zone was found near the flame edge, where both the lean and rich premixed flames and a diffusion flame coexisted. The flow pattern below the flame edge diverged radially due to a flow direction effect of the flame. Along the outer side of the flame, an inward entrainment was identified, probably caused by a buoyant acceleration of the flow in the burned region. The thermal thickness under the leading edge (the distance $a-b$ in Fig. 5) remained at $\sim 1\text{mm}$ for all

examined instantaneous flames, although the thermal layer became thicker in both the inward and outward radial directions along the premixed flame fronts affected by heat transfer from the flame.

Fig. 5. Definition of flame curvature, flame leading edge (point a), and the corresponding unburned location (point b). This also shows a general view of a flame shape, OH distribution, and flow pattern with $u_0 = 65\text{cm/s}$ at $V_{DC} = 10\text{kV}$.

The flame curvature at the leading edge (point a in Fig. 5) was a characteristic parameter for the instantaneous flame, since the propagation speed of a triple flame is governed by flow redirection effects due to the flame curvature [14–17]. Thus, the curvature (κ) was deduced by fitting the flame front as a polynomial function of degree 3 with a horizontal coordinate, x . Because $f'(a) = 0$ at the leading edge ($x = a$), the curvature can be calculated as $\kappa = |f''(a)|^2$.

The aforementioned processes used to determine the propagation speed of the flame edge could imply appreciable uncertainty in a rigorous quantification. First, the foremost flame edge was not necessarily the leading point of the whole flame, since the overall displacement of the flame was a result of the local velocity balance along a significant velocity gradient and mixture fraction gradient. Second, although the thermal thickness remained consistent throughout the experiment, the connection between the points a and b in Fig. 5 was weak in such a two-dimensional flow; there was no guarantee that a and b were in the same streamline. Similarly, the estimated unburned velocity varied depending on the location. We found that ± 1 pixel ($94.8\mu\text{m}/\text{pixel}$ in the present experiment) was the uncertainty in interpreting the recorded images. As a result, u_d showed less than 3% error, and u_u in the neighboring

pixels of the flame edge also showed less than 3% differences, indicating negligible systematic errors in the present study. A systematic error in determining the flame curvature was also small ($<5\%$). However, when $\kappa > 20 \text{ mm}^{-1}$, the estimated diameter of curvature ($< 100 \mu\text{m}$) from κ was comparable to the physical size of 1 pixel, thus, we excluded those corresponding data.

Although we tried to minimize the random errors through systematic analysis, the discussion below should be interpreted as a comparison among the displacement speed, the unburned velocity, and the resulting propagation speed of the flame edge.

Fig. 6. Flame displacement speed (a), unburned velocity ahead of a flame edge (b), and flame propagation speeds (c) for all tested conditions.

Propagating edge flames through non-homogeneous mixtures can be characterized by the mixture fraction gradient or flame curvature [15–17]. We hypothesized that when the stationary lifted flame propagated to the nozzle under the influence of electric fields, ionic wind would modify the

unburned flow and have a negligible impact on the combustion chemistry or flame intensity. In this regard, we analyzed the instantaneous and localized propagating characteristics under applied electric fields via the curvature of the flame, since the curvature controls the flow redirection and is closely related to the mixture fraction gradient that characterizes nonpremixed flames.

Figures 6a and 6b show the flame displacement speeds and the unburned velocity, respectively, as significantly scattered data. A displacement speed of zero indicated the initial stationary flames and the flames stabilized by the electric fields; all conditions that showed features of propagation to the nozzle were analyzed. Note that, a preliminary result for the case with $u_o = 35\text{cm/s}$ and $V_{\text{DC}} = -10\text{kV}$ analyzing both LHS and RHS of the propagating flame edge as shown in Fig. 4 indicated no significant difference in the propagation speed as a function of the flame curvature. Thus, only the lower sides of the flames were considered in the analysis. A few selected instants during a transient propagation for each condition are displayed in the figure for simplicity, and the fewer data with negative unburned velocity are partly due to excluding data with $\kappa > 20\text{mm}^{-1}$. We found that the displacement speed increased in all cases when electric fields were applied parallel to the propagation direction (as we hypothesized) and, due to the effect of ionic wind, we found negative unburned velocity even in the thermal layer.

However, we found a reasonably correlated trend overall between the flame propagation speed and the flame curvature (Fig. 6c) when we deduced the flame propagation speed using the data in Fig. 6a and 6b. The calculated laminar burning velocity of the mixture (S_L) and the theoretical maximum propagation speed in the limiting case of an infinitely large radius of curvature ($S_L(\rho_u/\rho_b)^{1/2}$) [14] are depicted at $\kappa = 0$ by open and closed circles (red), respectively, where ρ_u/ρ_b indicates the unburned to burned density ratio. The closed circular symbols (blue) indicate the stationary initial lifted flames, and the fitted curved line indicates those stationary flames that pass the theoretical maximum propagation speed at $\kappa = 0$, for comparison. We found that the instantaneous flame propagation speeds with electric fields were well correlated with the intrinsic edge flame propagation characterized by the

flame curvature, confirming that the applied electric field mainly affects the flow modification, and has a negligible impact on the combustion chemistry.

We may add general comments on the ionic wind in situations with electrical discharges, which can be referred as plasma assisted combustion. When a very short pulse of high voltage is considered (e.g. nanosecond pulse), the generation of ionic wind is not practically feasible due to a too short duration of electric field to create a bulk flow. However, as long as a duration of high voltage is sufficient (e.g. dielectric barrier discharges with AC), added ions and electrons due to the discharges will significantly increase the strength of the ionic wind.

4. Conclusions

Hypothesizing that an electric field parallel to the direction of flame propagation should increase the flame displacement speed, we designed a laminar lifted flame experiment. We confirmed three important facts. First, from a microscopic point of view, the electron impact attachment to oxygen molecules to form negative ions was supported by the PIV measurement. When the electron was a key player in the unburned zone, a gradual increase in negative velocity zone was caused by the finite rate of electron attachment during their movement toward the nozzle. On the other hand, a greater flow volume having negative velocity was found with the positive ions when negative voltage was applied to the nozzle.

Second and as expected, we found increased flame displacement speeds caused by significantly reduced upstream velocity. Third, we found that the flame propagation speeds could be characterized by the flame curvature (e.g., the local mixture fraction gradient) when they were estimated by the displacement speed and unburned velocity. This indicates that the effects of the electric fields were mainly reflected in the flow modification (unburned velocity variation), and the overall combustion chemistry was not likely to be affected by the electric fields. The present finding is consistent with the

previous results obtained with an orthogonal electric field [7,8], where reduced flame displacement was found with no significant change in propagation speed. Note that the present results should be effective to other hydrocarbon fuels, because the chemi-ionization process is initiated by CH radicals.

Future studies will address the beneficial utilization of the ionic wind. For example, since this method does not require any physical structures in a combustion zone and shows a faster *response time* than other flow control methods, it can be used for an active control method over a flame instability, such as thermos-acoustic instability.

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