Propagation of Tribrachial Flames in Electric Fields

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1 Introduction

Electric fields or plasma assisted combustion has been one of the interesting topics and the influence of electric fields on premixed and diffusion flames has been investigated extensively, including burning rate, flame stabilization, and emission reduction [1, 2]. These effects were frequently explained based on the ionic wind caused by the interaction of electric fields and ions existed in flames. Jaggers and von Engel [3] reported the augmentation of flame speed for hydrocarbon fuels from the experiments on the propagating premixed flames in a tube by applying both DC and AC fields, when the electric fields were orthogonal to the direction of flame propagation. It has been reasoned that the vibrational excited states of molecules could increase reaction rates. Marcum and Ganguly [4] reported the enhancement of flame speeds in premixed bunsen flames. They observed wrinkled laminar bunsen flames and suggested that the flame speed could be enhanced through the flame wrinkling in the electric fields caused by the diffusional-thermal instability due to the selective ion movements in reaction zone under DC electric potential.

Recently, the effect of electric fields on the reattachment of stationary lifted flame in coflow jets has been investigated [5]. It has been observed that the reattachment occurred at a higher jet velocity when an AC voltage was applied to the nozzle. The reason was attributed to the enhancement of the propagation speed of tribrachial edge by electric fields based on the observation of transient reattachment processes. The purpose of the present study is to elucidate further the effect of electric fields on the propagation speed of tribrachial edge. For this, we have conducted experiments for propagating tribrachial flames after ignition in coflow jets in terms of the applied voltage and frequency of AC and the applied voltage of DC.

2 Experiment

The apparatus consisted of a coflow burner and flow controllers, a power supply system, and a measurement setup. The coflow burner had a central fuel nozzle made of stainless steel with i.d. 0.254 mm and o.d. 1.588 mm. The nozzle length was 10 cm to ensure the fully developed parabolic velocity profiles at the nozzle exit and the nozzle tip was protruded 10 mm above the coflow exit. The coflow air was supplied to a concentric nozzle having i.d. 90 mm through glass beads and honeycomb for flow uniformity. The coflow velocity V_{CO} was fixed at 4.6 cm/s. The whole body of the coflow burner was made of acetal resin for electrical insulation, except the fuel nozzle. To prevent external disturbances, an acrylic cylinder with i.d. 90 mm and 25 cm in length was installed at the exit of the coflow air. The fuel was chemically-pure grade propane. The flow rates of the fuel and air were controlled by the mass flow controllers, calibrated with a wet-test gas meter.

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Both DC and AC power supplies were used. In case of AC, the frequency was controlled in the range of 60 to 1000 Hz by using a function generator to ensure the voltage pattern to be sinusoidal. The applied voltages were varied up to 10 kV in the RMS value. The voltage and current profiles were monitored by an oscilloscope, a 1000:1 voltage divider (Tektronix, P6015A), and a current probe (Tektronix, TCP312). The high voltage was applied to the central fuel nozzle, thus the nozzle served as an electrode terminal. The other terminal was connected to the building ground. The power consumption was found to be $O(1\ \text{W})$, thus the electrical Joule heating of the nozzle can be negligible. Details of the stability of electric fields were reported previously [5].

The system was ignited with electrical spark electrodes located 10 cm downstream of the fuel nozzle. Subsequent transient flame edge propagation toward the fuel nozzle was monitored with a high speed camera (Photron, Fastcam ultima 1024) with 250 fps. The displacement speed of tribrachial edge was evaluated from which the propagation speed of tribrachial flame has been determined [6].

3 Results and Discussion

Direct photographs of tribrachial flames during transient propagation to the nozzle after ignition are shown in Fig. 1 for the jet velocity of U_0 = 6.7 m/s. Although not clearly identifiable from the photographs, propagating edge flames were found to have a tribrachial structure, consisting of a rich premixed flame wing, a lean premixed flame wing, and a trailing diffusion flame, all extending from a single point [6]. The premixed flame wings dictate that a tribrachial edge has propagation characteristics. And the coexistence of three different types of flames indicates that the tribrachial point is located along the stoichiometric contour in the fuel and air mixing layer in a jet. It has been reported that the propagation speed of tribrachial flame edge is strongly dependent on the mixture fraction gradient or the fuel concentration gradient [6].

After igniting the system, the flame edge propagated toward the nozzle. Without having an electric field, the elapsed time was about 350 ms for the flame to become a stationary nozzle attached flame (a). The enhancement of the propagation speed with electric fields by applying AC voltage to the nozzle demonstrated (b) that the elapsed time decreased to about 270 ms, when the applied voltage $V_{a,AC}$ was 6 kV and the frequency was f = 60 Hz. This implies that the propagation speed of tribrachial flame under the electric fields was observed to be enhanced as compared to that without having electric fields.

The propagation speed of tribrachial flame edges without having electric fields has been measured experimentally in laminar jets [6]. The procedure was as follows. From the trace of edge height during transient propagation, the displacement speed S_d, which was defined as the time rate of change of edge positions, was determined. Then, the propagation speed of tribrachial flame S_e can be obtained from the vector summation of displacement speed and local flow velocity at the edge in such a way that $S_e = S_d + u_{st}$. Here, u_{st} is the local flow

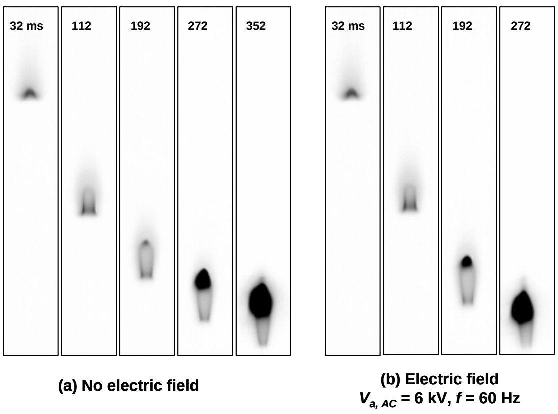

Figure 1. Instantaneous direct photos of propagating tribrachial flame for U_0 = 6.27 m/s; (a) without electric field, (b) with electric field when $V_{a,AC}$ = 6 kV, f = 60 Hz.

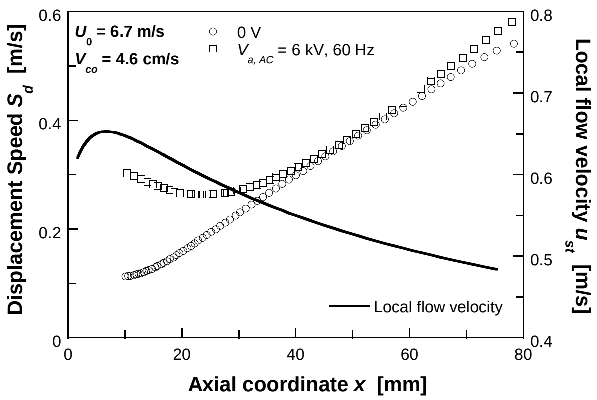

Figure 2. Local axial flow velocity along the stoichiometric contour and displacement speed of tribrachial flame with and without electric fields.

velocity and had been determined from the similarity solutions accounting for the virtual origins for velocity and concentration, the density difference between fuel and air, and coflow velocity [6]. The accuracy of the similarity solutions had been confirmed through velocity field and concentration fields measurements [6].

The displacement speed of flame edge S_d was determined from the derivatives of a polynomial curve-fit of the edge height with time. The results are plotted in Fig. 2 in terms of the axial coordinate x. Without applying the electric fields, the result shows that the displacement speed increases nearly linearly with the flame edge height represented as the axial coordinate x, as was observed previously [6]. While when the nozzle was applied with the AC voltage of 6 kV, the displacement speed exhibited significant increase as the edge approaches the nozzle, corresponding to small x. The axial velocity along the stoichiometric contour u_{st} is plotted with the axial coordinate in Fig. 2 as a solid line. Although the velocity near the nozzle can be calculated by adopting the similarity solution, however, the solutions are valid in the far field region. Consequently, the data for $x < 10$ mm were excluded in the following data reduction.

The propagation speed of tribrachial edge can be evaluated through the vector summation of displacement speed and local flow velocity as mentioned previously. The propagation speeds of tribrachial edges thus calculated are plotted in Fig. 3 in terms of the fuel concentration gradient dY_F/dR, where Y_F is the mass fraction of propane and R is the nondimensional radial distance, defined as the radial coordinate r divided by the radius of the nozzle r_0. The result shows that the propagation speed decreases monotonically when without having electric fields, while it decreases and then increases with the fuel concentration gradient where the electric fields were applied.

Without having electric fields, the propagation speed of tribrachial flame has been reported to be inversely proportional to the mixture fraction gradient [6], which can be represented by the fuel mass fraction gradient. Note that dY_F/dR represents the mixing layer thickness, which in turn determines the curvature of the premixed flame wings of a tribrachial flame [6]. Consequently, the flow redirection effect [6], arising from the streamline divergence by the curvature of the premixed flame wings, influences the local flow velocity, subsequently the propagation speed of the edge. In this regard, the edge speed was curve-fitted in terms of the inverse proportionality to dY_F/dR and shows a satisfactory representation of the experimental data for $V_{a,AC} = 0$. The extrapolated maximum propagation speed of the tribrachial flame is 1.09 m/s in the limit of $dY_F/dR|_{st} \rightarrow 0$, which agrees well with the theoretical prediction [6]. When the nozzle is charged with the AC voltage of 6 kV and frequency of 60 Hz, the propagation speed of tribrachial flame agrees with that for $V_{a,AC} = 0$ for small $dY_F/dR|_{st}$, which corresponds to the edge location far away from the nozzle. However, as the edge approaches the nozzle, that is, as $dY_F/dR|_{st}$ becomes larger, the propagation speed increases, from that for $V_{a,AC} = 0$, for example for $dY_F/dR|_{st} > 0.006$. This enhancement of the propagation speed near the nozzle can be attributed to the influence of electric fields. To elucidate the effect of electric fields on the edge speed, the propagation behavior of tribrachial edges was investigated by varying the voltage and frequency of AC electric fields, together with the voltage of negative and positive DC electric fields. And the results also showed similar enhancement on the propagation speed of tribrachial flame regardless of its current type and AC frequency.

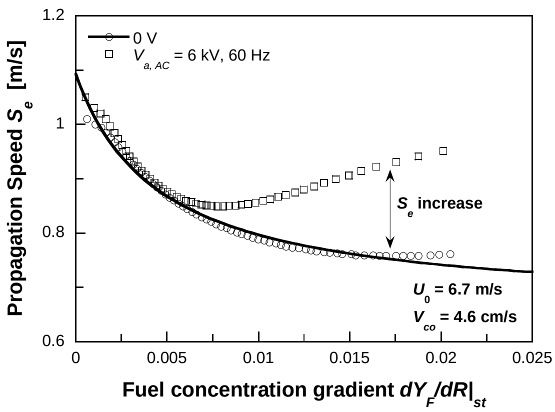

Figure 3. Propagation speed of tribrachial flame in terms of mixture fraction gradient with and without electric fields.

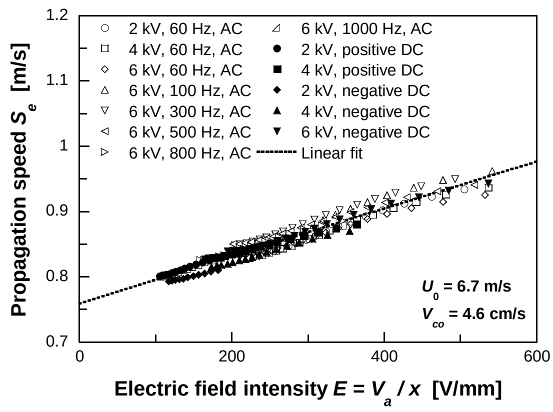

Figure 4. Correlation between propagation speed of tribrachial flame and electric field intensity.

To further investigate the effect of electric field intensity on the propagation speed of tribrachial flame edge, all the data for the AC and DC cases where the effect of electric fields on the propagation speed appear as the flame edges approach the nozzle, are plotted in terms of electric field intensity $E = V_a/x$ [V/mm] in Fig. 4. The results clearly show that the propagation speed of tribrachial flame edge can be correlated well linearly with the electric fields intensity to S_e [m/s] = 0.76 + 0.00036 E [V/mm], with the correlation coefficient of 0.96, which is marked as the dashed line. The result implies that the propagation speed of tribrachial flame edge is dominantly influenced by the electric fields intensity regardless of its current types as long as the electric fields intensity is varying, which is due to transient edge propagation in cases of DC charging.

4 Conclusion

The effects of electric fields on the propagation speed of tribrachial flame have been investigated systematically in coflow jet by tracing the transient flame propagation after ignition. The flame edge during the propagation exhibited a tribrachial structure, and the propagation speed of tribrachial flame showed inverse proportionality to the mixture fraction gradient as was previously reported. The behavior of flame propagation with the electric fields was observed with the single electrode method by connecting the high voltage electrode to the central fuel nozzle. The enhancement of propagation speed of tribrachial flame has been observed by varying the applied voltage and frequency for AC electric fields. The propagation speed of tribrachial flame was also investigated by applying negative and positive DC voltages to the central nozzle and similar improvements of the propagation speed were also observed. Finally, the propagation speeds of tribrachial flame in both AC and DC electric fields were correlated linearly with the electric field intensity.

Acknowledgement

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