Response of Counterflow Diffusion Flames to Low Frequency AC Electric Fields

B. C. Choi, H. K. Kim, M. K. Kim, J. H. Choi, and S. H. Chung,

School of Mechanical and Aerospace Engineering

Seoul National University, Seoul 151-744, Korea

1 Introduction

Electric fields could affect flame behavior in various ways. Charged particles existed in a reaction zone will be accelerated in electric fields by the Lorentz force, which could lead to the enhanced mobility of charged particles. The collision of the accelerated charged particles with neutral molecules transfers the momentum such that bulk flow can be generated, resulting in the ionic wind effect. Chemical reaction rate associated with charged particles can also be enhanced.

Among these effects by electric fields, the ionic wind effect has been investigated extensively, especially for diffusion flames. In the reaction zones of hydrocarbon flames, positive ions, including H_3O^+, $C_3H_3^+$, CH_3^+, and CHO^+, exist in the order of 10^9-10^{12} /cm^3 [1,2]. These ions are accelerated by electric fields. By random molecular collisions, the momentum can be transferred from accelerated ions to neutral molecules, such that the bulk motion of gas flow can be generated. In generating the ionic wind effect, there exists a delay time for the momentum transfer from accelerated ions to neutral molecules to activate bulk flow.

In the present study, the behavior of counterflow diffusion flames of methane diluted with nitrogen has been investigated experimentally by applying AC with the frequency lower than 100 Hz. The oscillation behavior of the diffusion flame will be reported.

2 Experiment

The apparatus consisted of a counterflow burner and flow controllers, an AC power supply, and a visualization setup. The counterflow burner had two divergent-convergent nozzles with the area ratio of 36:1 to obtain a near-uniform velocity profile. Fuel and oxidizer were supplied in opposed directions through the nozzles with i.d. 10 mm to form a counter flow diffusion flame. The distance between the two nozzles was fixed at 16 mm. The fuel was the mixture of chemically-pure grade methane (>99.98%) and nitrogen diluent (>99.99%) to suppress soot formation. The oxidizer was the mixture of 21% O_2 and 79% N_2. Nitrogen was also used as shield gas to prevent outer disturbance by supplying through concentric slits at the nozzle exits. The flow rates of the fuel and oxidizer were controlled by mass flow controllers calibrated with a wet-test gas meter. The nozzle exit velocities were fixed at 30 cm/s and the fuel mole fraction of $X_{F,0} = 0.3$.

An AC power supply (Trek, 10/10B-FG) and a function generator (NF, WF1943B) were used to apply voltage. The high voltage terminal from the power supply was connected to one of the circular meshes having 60 mm in diameter placed at the exit of the nozzle. The other meshes and the ground terminal from the power supply were connected to the building ground. The meshes have much larger diameter than those of the nozzles to maintain reasonably uniform electric fields. The voltage profile was monitored by an oscilloscope (Tektronics, TDS 1012B) and a 1000:1 voltage divider (Tektronics, P6015A).

Correspondence to: chbych@snu.ac.kr

The applied AC voltage was varied up to 7 kV in the RMS value. The frequency was controlled in the range of 0.1-100 Hz. The flame images were taken by a high speed camera (Photron, Fastcam Ultima 1024) with the maximum of 500 fps. The response of the diffusion flame with varying electric fields was monitored and represented by the flame position along the centerline, which was defined as the location of maximum luminosity.

3 Results and Discussion

The response of the counterflow flame to AC electric fields has been monitored. There exist three typical responses of the diffusion flame to the AC electric fields depending on the frequency and voltage of AC, as illustrated in Fig. 1 for the fixed AC voltage of V_{ac} = 1.5 kV with the frequency of f_{ac} = 100, 8, and 0.2 Hz. First, for f_{ac} = 100 Hz (a), the flame exhibits a typical diffusion flame in a counterflow, by maintaining its shape and position nearly fixed in space at the distance of 8.31 mm from the fuel nozzle. This flame position is the same as that without applying electric fields. The time variation of the flame position along the centerline indicates that the flame position is minimally influenced by the AC electric fields at this high AC frequency.

Second, for the intermediate AC frequency of f_{ac} = 8 Hz (b), the diffusion flame oscillates. The flame images are represented with the interval of the phase angle of 90°, which is defined from the minimum position. The flame image at the phase angle of 270° is quite similar to that of 90°. The flame length in the horizontal direction somewhat varies with the phase angle, which can be attributed to the flow field variation together with the flame oscillation. The period of oscillation is 125 ms, which corresponds to the oscillation of 8 Hz AC electric fields. Thus, the flame oscillation is synchronized to the AC frequency. The oscillation of the flame position is reasonably sinusoidal with its maximum and minimum values of 10.8 and 7.4 mm, respectively, such that the peak-to-peak amplitude is 3.4 mm.

For the low frequency of f_{ac} = 0.2 Hz, the flame response is quite complex, as represented in Fig. 1c, where the flame images with the time interval of approximately 5/6 s are exhibited. The variation of the flame position along the centerline demonstrates complicated behavior with several spiky modes, marked as A to E. Slightly tilted non-axisymmetric flame and U-shaped flame are observed during the oscillation. The maximum and minimum values in the flame positions are 11.6 mm and 4.4 mm, respectively, with the amplitude of 7.2 mm. The flame also exhibits weak fluctuations near the maximum positions (D), where the flame has a U-shape. The response may be related to the response of the flame to DC electric fields, that is, the diffusion flame may experience the voltage variation of AC as if it is a quasi-DC. Further investigation is needed by applying DC electric fields.

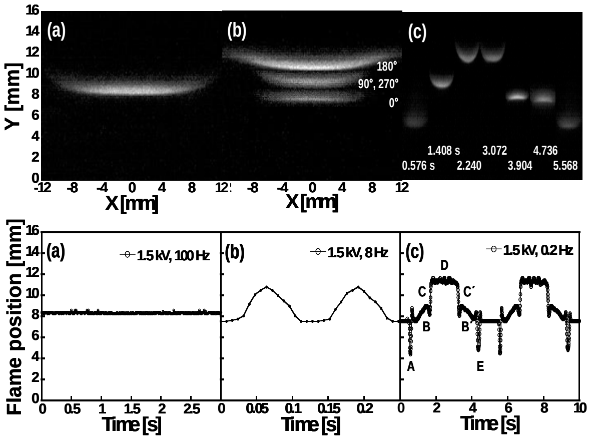

FIG. 1. Direct photos and flame positions with time for V_{ac} = 1.5 kV: (a) f_{ac} = 100 Hz, (b) 8 Hz, and (c) 0.2 Hz.

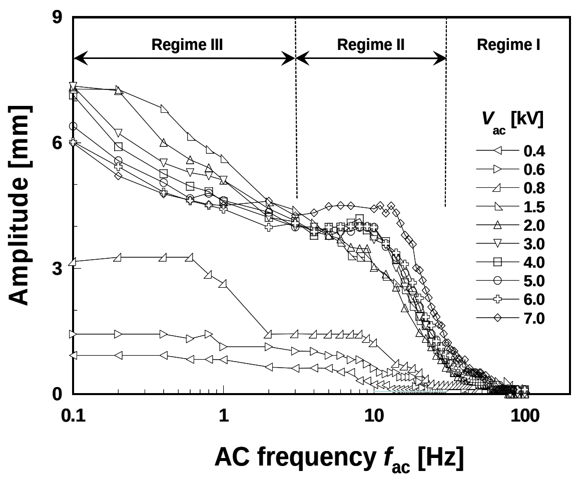

FIG. 2. Oscillation amplitude with frequency at several voltages

The peak-to-peak amplitude of oscillation determined from the maximum and minimum positions is shown in Fig. 2 as a function of the AC frequency in the range of 0.1-100 Hz at several voltages up to 7 kV. Three typical regimes of oscillation in terms of AC frequency are exhibited. In the high frequency regime I with $f_{ac} = O(100 \text{ Hz})$, the oscillation amplitude is negligibly small, typically much less than 1 mm. In the intermediate frequency regime II with $f_{ac} = O(10 \text{ Hz})$, the oscillation amplitude increases with the applied voltage. In the low frequency regime III with $f_{ac} = O(0.1\text{-}1 \text{ Hz})$, the amplitude increases with the applied AC voltage up to say 1.5 kV, and then decreases.

The transition between the high and intermediate frequency regimes is an indication of the onset of oscillation as the frequency decreases, thereby the existence of a threshold frequency. Together with this, the oscillation behavior of the intermediate AC frequency regime will be further analyzed in the following.

This oscillation behavior can be understood based on the ionic wind effect, which arises from the momentum transfer to neutral particles by the collision with charged particles of ions, thereby the generation of bulk blow field. The ions exist in a chemical reaction zone in the order of 10^9-10^{12} /cm^3 [1]. In electric fields, the ions will be accelerated by the Lorentz force qE, where q is the electric charge of particle and E is the electric field intensity, which is proportional to the applied voltage. Under uniform electric fields, the ions will be accelerated linearly with time. Due to random molecular collision with the collision frequency Z, the accelerated ions are expected to lose its momentum to neutral particles. As a consequence, the drift velocity of ions can be generated, which will be proportional to qE/Z, and so does the momentum transfer.

Applied AC voltage has both positive and negative polarities. Thus, the period of acceleration of ions is limited to $1/2f_{ac}$. Note that the AC frequency in the present experimental range is much smaller than the collision frequency. Therefore, as the AC frequency increases, the effective duration for the momentum gain by ions and thus the momentum transfer to neutral particles will decrease. Consequently, the increase in the applied AC voltage and the decrease in the AC frequency will enhance the ionic wind effect.

If the ionic wind effect is generated in a reaction zone of a diffusion flame in a counterflow, the stagnation plane will be modified such that the flame can oscillate. The argument based on the ionic wind effect could qualitatively understand the oscillation behavior in the intermediated frequency regime where the oscillation amplitude increases with the voltage increase and frequency decrease. The drift velocity of charged particles will induce the mobility such that a directional diffusion of charged particles can be enhanced. Simultaneously, it will enhance the kinetic energy of charged particles, such that ion- or electron- induced reaction may be promoted. Respective effects on flame behavior have not been fully quantified yet and future studies are required.

As mentioned previously in Fig. 2, the diffusion flame oscillation ceases at high frequency in the order of 100 Hz, such that there exists threshold frequencies. Based on the response of the oscillation amplitude, the threshold frequency is determined as follows. The inset in Fig. 3 explains the procedure. For example, at $V_{ac} = 6.0$ kV, the maximum gradient in the amplitude-frequency relation is determined, which corresponds roughly to the inflection point. Then, the maximum gradient has been utilized in determining the threshold frequency from the extrapolation to the zero amplitude.

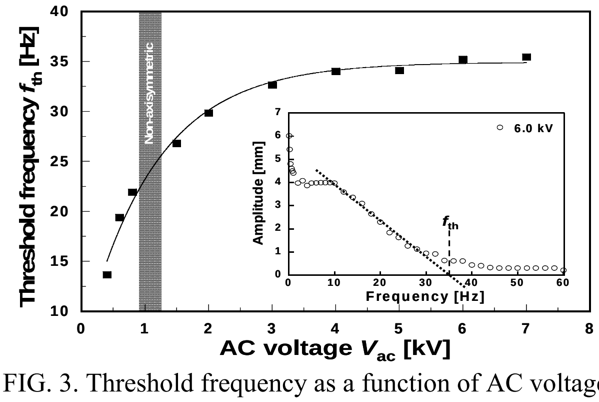

FIG. 3. Threshold frequency as a function of AC voltage

This threshold frequency is plotted in terms of AC voltage in Fig. 3. The result shows that the threshold frequency increases with the voltage and then levels off. The best fit is f_{th} = 34.925 - 28.477 exp(–0.889 × V_{ac}) with the correlation coefficient of R = 0.995, where f_{th} and V_{ac} are in [Hz] and [kV], respectively. Note that in the range of $0.9 \leq V_{ac} \leq 1.2$ kV, the flame has non-axisymmetric shape by having a slanted flame at the center axis and oscillates. However, the threshold frequency based on the flame position along the centerline is in accordance with the correlation.

The threshold frequency in the limit of large V_{ac} is 34.9 Hz from the curve fitted data. The present limiting threshold frequency of about 35 Hz can be explained based on the collision response time [3,4]. It has been previously suggested that for the ionic wind effect to occur, there exists a delay time for a flow field to respond. This corresponds to the collision response time $t_c = (n_0/n_i) / (1.4\pi\sigma^2 v_m n_0)$, where n_0 and n_i are the number densities of neutral molecules and ions, respectively, σ is the collision diameter, and v_m is the mean molecular velocity. For a realistic flame situation, it has been estimated to be about 14 ms [5]. Considering the change in the polarity of AC, which determines the direction of the ionic wind effect, the time scale for the acceleration of charged particles is $(1/2f_{ac})$. With the present threshold frequency of about f_{th} = 35 Hz, the time scale of $(1/2f_{th}) \approx 14$ ms is in good agreement with the previous estimation [5].

This result implies that for $f_{ac} > f_{th}$, the diffusion flame oscillation can be minimal, since there is insufficient time for the ionic wind effect to be generated. The proposed collision response time does not contain the effect of the variation of AC voltage. The present result in Fig. 3 shows that the threshold frequency is influenced by the voltage, especially when the applied voltage is small. This is reasonable based on the previous argument on the ionic wind effect considering AC frequency on the acceleration of ions, drift velocity, and momentum transfer to neutral particles. Note that as the AC voltage increases excessively, a corona discharge could occur. Then, the flow field is expected to be disturbed by the generation of streamers.

4 Concluding Remarks

The effect of electric fields on the diffusion flame of methane with diluted nitrogen in the counterflow has been investigated experimentally by varying the applied voltage and frequency of AC. There exited three types of flame responses with AC electric fields. In the high frequency regime with $f_{ac} = O(100$ Hz$)$, the flame was typically stable with negligibly small response. In the intermediate frequency regime with $f_{ac} = O(10$ Hz$)$, where the oscillation amplitude increased with the voltage increase and frequency decrease, the flame oscillated nearly sinusoidally by the ionic wind effect. And the threshold frequency existed based on the collision response time. The present threshold frequency in the high voltage of about 35 Hz corresponded to the collision response time of about 14 ms. In the low frequency regime with f_{ac} = O(0.1-1 Hz), the response of the diffusion flame exhibited complex behavior. The response may be related to the response of the flame to DC electric fields. Further investigations are needed by applying DC electric fields.

Acknowledgement

This work was supported by HKCRC through IAMD.

References

[1] J. Lawton and F. J. Weinberg, Electrical Aspects of Combustion, Clarendon Press, Oxford, 1969.

[2] F. J. Weinberg, Advanced Combustion Methods, Academic Press, 1986

[3] M. Kono, K. Iinuma and S. Kumagai, Proc. Combust. Inst. 18 (1981) 1167-1174

[4] M. Kono, F.B. Carleton, A.R. Jones, and F.J. Weinberg, Combust. Flame 78 (1989) 357-364

[5] L. Sun, G. Lins, and T. Hammer, Proc. European Combust. Meeting, 2005