The Reattachment Process of Turbulent Lifted Diffusion Jet Flames Induced by Repetitive D.C. Electric Pulse Discharges

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1 Introduction

The growing concern of fuel economy has created the need to develop an advanced combustion system of high energy efficiency and low pollution emission. Fuel lean combustion is an adequate timely solution to fulfill the need. In general, lean combustion process has its inherent problem of flame instability, which leads to unstable flame behaviors such as liftoff and blowout in non-premixed diffusion jet flame and unstable extinction in premixed flame. Thus, the flame stabilization in numerous practically combustion devices is an important issue and how to enhance flame stability with more efficient methods and low cost apparatus is always an ultimate goal.

Electrically enhanced combustion by applying electrical field or plasmas has been extensively investigated for improvement of flame stability and reduction of pollutant emission. Thus, numerous studies have been performed to look into the effects of the electric field on the flame stabilization, especially for extension of the liftoff stability limit of non-premixed turbulent jet flame [1-2], and increase in propagation speed of tribrachial flame in laminar coflow jets. In regard to enhanced flame stability, the apparent effect of electric fields on attached diffusion jet flame can be observed when the high-voltage alternate current (AC) with various frequencies are applied to a nozzle of propane fuel. The reported results indicate that the flame liftoff velocities increase and liftoff heights decrease with increasing applied voltage and frequency of AC charging, meaning that the stabilization regime can be extended by AC electric field discharges. Similarly, for a laminar lifted jet flame, the reattachment velocity also can be enhanced by applying AC electric field to the flame edge, which increases linearly with applied voltage and decreases with an increase in frequency, nevertheless, the stationary liftoff heights are not affected by AC discharges [2]. On the contrary, the enhanced efficacies are both insignificant as applying direct current (DC) voltages to the nozzle to produced DC electric field discharges. However, Won et al. [3] indicated that the propagation speed of tribrachial flames edge can be enhanced by increasing both AC and DC electric field intensities, but is insensitive with AC frequency. The authors also note that the difference in improvement of propagation velocity between positive and negative DC electrical fields may be attributed to the ionic wind effect. Furthermore, Belhi et al. [4] verified numerically that this ion-driven-wind hypothesis can serve to explain flame stabilization enhancement as applying DC electric field longitudinal across to a turbulent lifted flame with two types of polarity, and suggested that the calculated electric force induced by electric field in the upstream of flame base is the reason for decrease in flame liftoff height.

For plasma effect, the repetitive pulsed-gas discharges have been found easier to produce abundant active and electronically excited species than DC or AC electric field discharges that promote generation of active radicals in the flame reaction zone leading to enhanced lifted flame

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stabilization. The reduced flame liftoff height and enlarged blowout velocity have been obtained with the application of fast-rise-time DC pulsed dielectric-barrier discharges (DBD) with pulse repetition frequency (PRF) of 200 Hz and positive polarity to the upstream of lifted flame base [5]. In addition, by employing DC high-voltage of negative polarity between two electrodes [6] and high-frequency (25~35 kHz) AC charge with single electrode configuration [7], it both can generate an apparent corona plasma near the powered electrode, which improving premixed jet flame stability and blowoff velocity of lift flame, respectively. The results show that the presence of a diffuse corona discharge from powered electrode to the lifted flame base is a potential stabilization enhancer.

Regarding the stabilization mechanism of the lifted turbulent jet flame, the evolution of the leading-edge flame concept and the model of the tribrachial (or triple) flame have been the subjects of a series of intensive arguments and advanced experimental and numerical examinations [8-11], and the model has become popular and generally accepted. From above reviews, it is found that the reattachment result of a stationary laminar lifted flame is inconsistent with the enhancement of the tribrachial flame propagation velocity by DC electric field, as a result, it represents the understanding of the interaction between pulsed-DC electric field or pulsed-corona discharge and leading-edge flames is rather limited currently, and the effects of the electrode polarization is still uncertain. Thus, the objective of this work is to characterize experimentally the stabilization behaviors of lifted turbulent jet flames under the effect of DC electric pulse discharges featuring different polarities with a single electrode configuration and to describe the dynamic response of the flame base to applied various PRFs.

2 Experimental Methods

In order to investigate the effects of pulsed-DC electric discharge with different polarities on the reattachment and stabilization characteristics of a lifted turbulent diffusion jet flame, the experimental apparatus consists of a quartz-tube burner with a fuel supply system for generating a stationary turbulent lifted jet flame, a repetitive high-voltage pulse generator for pulsed-gas discharge in the downstream region of the jet, and a high-speed video camera to record instantaneous leading edge flame images for analysis. The volumetric flow rate of fuel stream provided from a propane cylinder with a regulator can be controlled by a well-calibrated rotameter. The burner is a straight circular quartz-tube of 3 mm in inner diameter and a length-to-diameter ratio of 150 to ensure fully-developed condition at tube exit. The investigated propane exit velocity ranges from 4 m/s to 12 m/s, corresponding to the Reynolds number approximately from 2600 to 7800. The nozzle is surrounded with a mesh confinement to prevent external flow disturbances.

In general, the electric field intensity is defined as the ratio of applied electric voltage to the distance between two discharging electrodes, and the corona plasma is ignited when the intensity exceeds a critical value. A small diameter brass cylinder with a sharp tip as the electrode was used to apply electric field of different polarities and to generate steady corona plasma, which is connected to the high-voltage terminal of the pulse generator, and the high-temperature lifted-flame serves as a virtual electrode. The electrode radial location, R, offsetting the distance of 1.5 times tube inner diameter, D, from jet centerline is choosed and implemented with an angle of 45 degree to avoid jet flow disturbance. The pulse electric power applied at the electrode by the high-voltage pulse generator can be measured by simultaneously using a high voltage probe (Pintek HVP-15HF) and a Rogowski Coil (Pearson, model 150). The applied single voltage pulse can vary up to ±15 kV of peak value with fix duration of 80 μs, and the measured maximum power consumption is less 7.5 W. The schematic diagram of the experimental setup is shown in Fig. 1, indicating two triggering pulse generators were used to trigger and activate the high-speed video camera (PCO1200HS) and the high-voltage DC pulse generator with various polarities. For the current experiments of the reattachment process and flame stabilization behavior of a lifted flame, it was found that a high framing rate of 500 Hz for the high-speed camera has to be used to synchronize and freeze the flame base motion in conjunction with high-voltage pulse of 100, 200, 400, 800, 1250 Hz and 1500 Hz for the generator. A sequence of 500 instantaneous flame images with exposure time of 2 ms after discharge initiation are recorded and evaluated by using the digital image processing for the dynamic flame response to repetitive pulse discharges.

The instantaneous velocity field at the turbulent lifted flame base has been used to interpret various flame edge stabilization characteristics. Hence, the shuttered PIV system [12] is utilized for instantaneous planar velocity measurements at the flame base under repetitive electric pulse discharges. The shuttered PIV system includes two pulse Nd:YAG lasers, a 1360 × 1024-pixel high-sensitivity CCD camera (Pixelfly 220XD) equipped with double-exposure function to detect the scattering images, a mechanical shutter collocated in front of imaging lens of the CCD camera to acquire the distinguished particle images and a TiO_2-particle seeding system to generate seeding particles. In the same way the CCD camera system, two laser pulses, and the high-voltage pulse generator are synchronized and activated to image the instantaneous velocity profiles at specific delay times after discharge initiation.

3 Results and Discussion

For the flame instability scenario of the attached-liftoff-blowout process of a turbulent non-premixed jet flame subject to increase of jet exit velocity, a lifted flame can be stabilized at a favorable downstream location in the liftoff region, and reattachment of the lifted flame may occur when decreasing the jet exit velocity, Ve, lower than the flame reattachment velocity. Thus, hysteresis phenomenon usually is found before reattachment from lifted-flame type. The reattachment velocity of 5 m/s can be observed from the case without electric pulse discharges. To examine the influence of pulsed-DC electric discharge on the lifted flame edge reattachment, in present study the original lifted flames,at various Ve, are established by flame propagation and stabilization after igniting the fresh mixture from a downstream location, and followed repetitive high-voltage electric pulses of positive or negative polarity with 15 kV peak value is applied to the electrode. Figure 2 illustrates the effects of pulsed discharges with various PRF on the flame stabilization enhancement for two polarity cases as compared to the reattachment velocity for the case with PRF = 0, indicated by an open circle in the figure. The region below the solid lines represent that lifted flame base can reattach to the nozzle rim for two various polarities separately. When Ve is increased, flame stability can be enhanced. Result shows flame reattachment enhancement in terms of Ve by increasing PRF up to 1500 Hz for positive polarity case. Apparently, Ve increases monotonously with PRF, from 5 m/s to 11 m/s as PRF is increased from 0 to 1500 Hz. In contrast, for the negative polarity cases the maximum Ve enhancement is only increased to 7 m/s by increasing PRF.

Further close look into the transient reattachment process of the lifted flame under the influence of D.C. electric pulse of positive polarity is performed by using a high-speed video camera. Figure 3(a) and (b) shows the sequence high-speed images of lifted flame reattachment at a jet exit velocity of 10 m/s during transient upstream propagation after applying positive DC pulse for PRF= 200 and 1500 Hz, respectively, with the electrode location R = 1.5 D indicated by a sharp white cone in the figure. The reattachment process in Fig. 3(a) and (b) shows that immediately after applying the DC pulse the flame base moves slightly upstream, becomes slanted after about 40 ms from the initial pulse, starts to propagate upstream along the electrode side and extends further upstream till relocating itself at the burner rim especially for the 1500 Hz case in Fig. 3(b). When the flame base located near the electrode side propagates to a single electrode, the corona plasma could discharge at the electrode tip and be observed between the cusp-like pointing flame edge and the electrode, which is indicated by a white arrow symbol in the Fig. 3. It is a direct introduction of electric/plasma power into the flame base to enhance flame propagation during reattachment process.

From a series of flame base propagation images, initiation of the corona discharge can be observed at different specific times for different PRF conditions. For better understanding of the effect of pulse frequency on flame reattachment, detailed dynamic flame edge response to positive electric pulse discharges with various PRFs is illustrated in Fig.4. Figure 4 is a plot of the instantaneous height of the most upstream point at flame base versus time during the propagation process for PRF of 200 and 1500 Hz, determined from the high-speed video images. Likewise, the displacement speed of the flame bases can be evaluated from the time derivatives of the flame base heights, and the results are plotted with time and superimposed in the same figure. The red dash-dot line in the figure represents the moment at which the initiation of the corona discharge is observed in the corresponding sequence of images. For higher PRF case, the final flame base heights are less than 1 mm from the burner rim. It is apparent that the time elapsed for flame base reattachment to the burner is reduced with an increase in PRF, and the maximum displacement speed is increased close to 0.38 m/s and 1.1 m/s for PRF of 200 Hz and 1500 Hz respectively when the flame base propagates close to the burner (or the electrode). The results of variation in displacement speed with time indicate that when generating the corona discharge between flame edge and electrode, the peak values of the flame base displacement speed exceed the laminar burning velocity of propane/air premixed flame in stoichiometric condition, which is about 0.4 m/s. This implies that the displacement speed of flame base after initiation of the corona discharge is enhanced beyond the laminar burning velocity for higher PRF, thus, leading to flame reattachment.

To interpret the effect of applied corona discharges on flame fluidics in the reattachment process, a planar PIV measurement was performed to examine the flow structure and velocity field in the vicinity of flame base as shown in Fig. 6. The burner operating condition is jet exit velocity of 10 m/s and the velocity field is detected at the specific time of 40 ms, occurring corona discharge, by PIV CCD after initiating electric pulsed-discharge sequences for PRF of 1500 Hz case. The plotted arrows display the velocity direction and its length indicates the corresponding velocity magnitude, in addition, flame base outline is also marked by black solid-line in this figure. It is well-known that the instantaneous gas velocity magnitude in the upstream of flame base without electric discharge is around 0.4 m/s. Apparently, the instantaneous gas velocity magnitude detected at flame base located farther away from electrode is approximately equal to stoichiometric laminar burning velocity, but which approaches to 0.1 m/s at where near electrode side. The result suggests that the corona discharges could modify velocity field in the vicinity of flame base locally, which is even below laminar burning velocity, thus, would benefit the leading-edge flame propagation.

4 Conclusion

The stabilization enhancement of a turbulent lifted propane-jet flame by applying the repetitive high-voltage electric pulses to the single electrode with various discharge polarities has been experimentally investigated through the observation to the flame-base reattachment process. The enhanced efficacy is more significant for applying voltage pulses of positive polarity with higher PRFs. High-frame-rate flame base trace and PIV results indicate that flame base cannot reattach to the burner rim for the low PRF case as the peak displacement speeds are less than 0.4 m/s. On the contrary, the drastic increasing of displacement speed is found for higher PRF (above 800 Hz) case, and the maximum speed magnitude approaches to 1.1 m/s. This implies that the displacement speed of flame base after initiation of the corona discharge is enlarged above the stoichiometric laminar burning velocity for higher PRF and positive polarity, thus, leading to flame reattachment. In addition, the corona discharges could modify the instantaneous velocity field in the vicinity of flame base and decrease velocity magnitude below the laminar flame speed, so as to provide the advantage of flame reattachment.

5 Figures

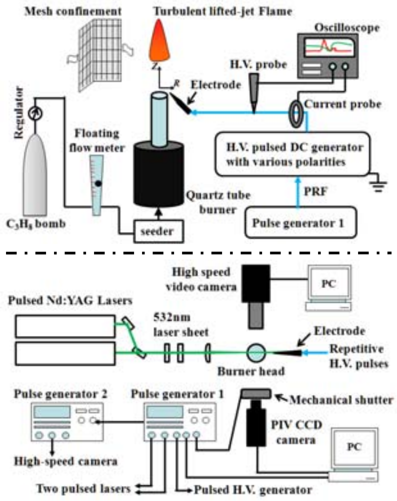


Figure 1. Schematic diagram of experimental setup including quartz-tube burner, pulsed-DC discharge system, shuttered PIV system, and high-speed video camera.

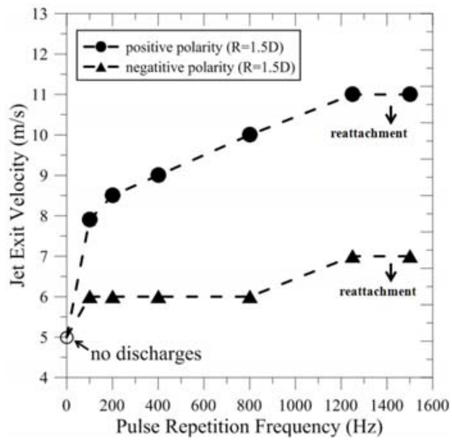


Figure 2. Flame reattachment enhancement by repetitive pulsed-DC electric discharges with various pulse repetition frequencies for two different applied polarities. The applied voltage peak values are both 15 kV.

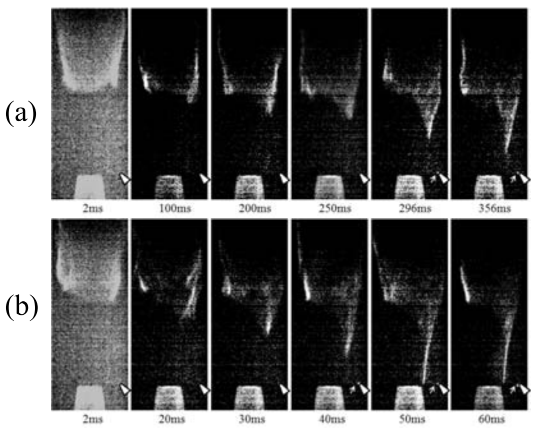
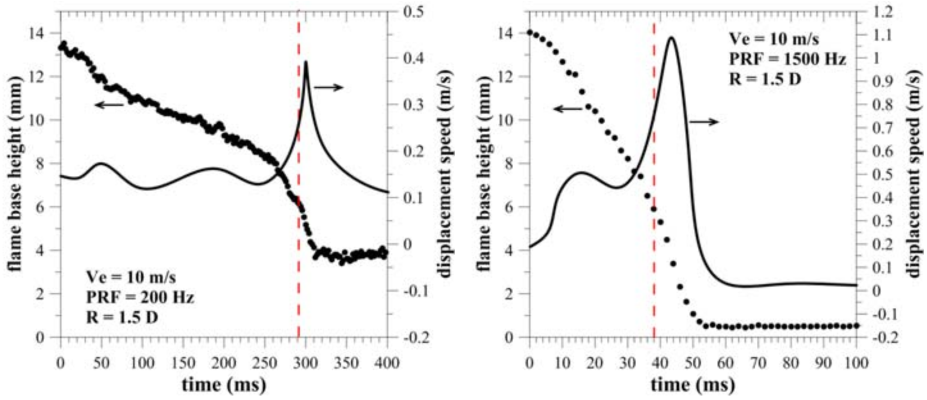


Figure 3. Instantaneous photographs of propagating flame edges for Ve = 10 m/s with application of positive polarity discharges at R= 1.5 D and various PRFs: (a) 200Hz (b) 1500Hz. The corona discharge appearance is indicated by symbols of white arrows.



(a) (b)

Figure 4. Temporal evolution of the flame base height plotted with displacement speed during flame propagation for Ve = 10 m/s with applying positive pulsed-DC discharges at R= 1.5 D and various PRFs: (a) 200Hz (b) 1500Hz. The time of corona discharge appearance is indicated by red dash-dot lines.

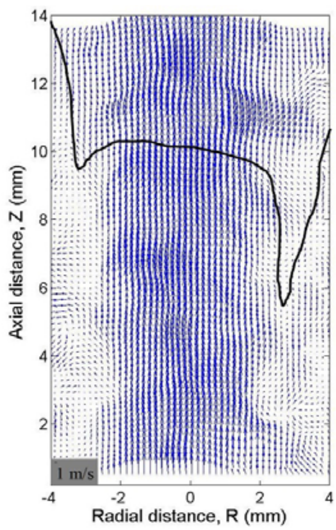


Figure 5. Instantaneous velocity field distribution of gas flow in the vicinity of flame base for Ve = 10 m/s by 2D PIV measurement at 40 m/s after initiation of electric pulse discharges with PRF of 1500 Hz. The black solid-line represents the instantaneous flame base outline. The radial location of electrode is R = 4.5 mm on the right side of figure.

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