The effect of pulse electric discharge on the stabilization of turbulent lifted jet flames

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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 blowoff in non-premixed diffusion jet 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 is always an ultimate goal.

Electrically enhanced combustion by applying electrical field or plasmas has been extensively investigated for improvement of fundamental combustion behaviors, such as ignition, flame propagation, and stabilization. Studies on the influence of electric field on flame characteristics involving extension of the stability limit and the propagation speed of tribrachial edge in non-premixed jet diffusion flame and lifted flame respectively have been performed [1-4]. In regard to flame stabilization, enhanced stability characteristics by applying AC electric field with various high voltages and frequencies to a single-electrode in a turbulent non-premixed jet flame can be observed [1].On the contrary, the efficacy is insignificant when applying DC electric field to the flame. The reported results show that the flame liftoff velocities increase and liftoff heights decrease with increasing voltage and frequency of AC electric field, meaning that the range of stability can be extended by AC discharge. Similarly, the effects of AC and DC electric fields on the stabilization characteristics of non-premixed laminar propane-jet flames in a coflow have been investigated experimentally [2]. The results demonstrate that the stabilization regime of nozzle-attached jet flame can be enlarged with AC charging and for DC cases have only a minor effect. The authors also suggest that the enhanced ability by applying AC electric field is varied with the voltage and frequency, which is explained and attributed to the appearance of electrical corona discharge as increasing either AC voltage or frequency to a specific critical value. It is interesting to note that the corona discharge would reduce the effects of AC electric field on jet-flame stabilization, resulted from flow disturbance between the nozzle exit and attached-flame edge. In consequence, the correlation of liftoff velocity with applied voltage and frequency of AC charging is suggested in the corona-free electric-field-enhancement regime, and in this regime the enhancement mechanism are mainly due to the effect of ionic wind, for which the strength is determined by electric field intensity. On the other hand, the stability of lifted turbulent methane-jet flames can both be enhanced by using the repetitive pulsed-gas discharges [5] and high-frequency (25~35 kHz) of AC charging [6] to generate non-equilibrium plasma with the electrode located above nozzle. This type of plasma discharge usually produces active and electronically excited species in ultrashort durations (10~100 ns) with the high pulse repetition frequency (15 kHz) and high-voltage DC (6 kV), referred to as ultrshort-pulse repetitive discharge

(USRD), which can promote growing of active radicals in the flame, leading to enhancement of flame stabilization. The decreased flame liftoff height and increased liftoff velocity can also be obtained with the single electrode corona discharges (SECD) powered by AC [7]. The results show that the presence of a diffuse corona discharge from powered electrode to the flame base is a potential stabilization enhancer.

The scope of the present study is focused on the effects of electrical discharges on the stabilization of turbulent lifted propane-jet flames in the still air. The liftoff height and liftoff velocity are representative properties for flame stabilization in practical combustors. When liftoff height is reduced, flame stability can be enhanced. As mentioned above, the effects of enhanced combustion by applying AC electric field to the fuel nozzle and USRD on the flame stability have been extensively investigated, but detailed understanding of the interaction between pulse-DC electric field/corona discharges and lifted jet-flame is rather limited. Thus, the objective of this work is to characterize experimentally the effects of repetitive pulsed electric field/corona discharges with SECD configuration on the stabilization of lifted turbulent jet flames and to describe the dynamic response of the flame base to applied pulse repetition frequency.

2 Experimental Methods

The experimental apparatus shown schematically in Fig. 1 are used to investigate the effects of repetitive pulsed electrical discharges on the stabilization characteristics of turbulent, lifted jet diffusion flames. It consists of a quartz-tube burner with a fuel supply system for generating the turbulent lifted jet flame, a repetitive pulsed high-voltage generator for creating the negative electric field with SECD configuration, and a high-speed video camera for recording a series of instantaneous images of turbulent lifted flame base. The volumetric flow rate of fuel stream provided from a liquid propane cylinder with a regulator can be controlled by a well-calibrated floating flow meter. Propane gas is injected through a straight circular quartz-tube with an inner diameter of 3 mm and a length-to-diameter ratio of 150 to ensure fully-developed turbulent flow at tube exit. The investigated jet exit velocity ranges from 4 m/s to 12 m/s, which are evaluated approximately from 2600 to 7800 of Reynolds number. In general, the corona discharges are generated by strong electric field associated with the needle, or sharp edge on an electrode, and the type of which depends on the polarity of applied high-voltage power. It is also reported that more powerful corona discharge can be produced with pulse-DC charging, and indicated that the rise time of the pulse is a key point [8]. By considering this, the present work employs a small diameter stainless-steel wire with a sharp tip as the power electrode which connects to high-voltage terminal of pulse generator, and the high-temperature lifted-flame base itself serves as a virtual electrode. To avoid disturbing the jet flow development by the powered single electrode, the electrode is placed at the location away from jet centerline by three times of tube radius and at an angle of 45 degrees, which is much wider than the thickness of the boundary in turbulent free-jet [9]. The electrode is fixed on a vertical translator for adjusting location height above the jet exit plane at the height of 0 and 0.25 H_L, where H_L is the measured mean liftoff height without electrical discharges. In addition, the deposited electric energy in the medium provided by high-voltage pulse generator can be calculated from the pulse voltage and current signals at the electrode, which are detected on a digital oscilloscope by simultaneously using a high voltage probe (Pintek HVP-15HF) and a Rogowski Coil (Pearson, model 150) respectively.

The mean liftoff heights at various jet exit velocities with applying repetitive pulsed high-voltage discharges can be measured by employing two pulse generators to trigger the high-speed video camera (PCO1200HS) and the high-voltage pulse generator is synchronized with a sufficiently high repetition rate of 200 Hz for camera to freeze the flame base motion and of 50, 100, 160, 200, 320, 400, 500, and 800 Hz for discharge generator respectively. A sequence of 200 instantaneous flame images with exposure time of 4 ms within 1 sec can be recorded and evaluated by using the digital image processing to obtain the mean liftoff height.

3 Results and Discussion

As indicated above, the pulsed corona discharges are probably occurred at the tip of a power electrode with a high-voltage pulse while the lifted flames are regarded as the grounded electrode. Thus, through the measurement method shown in Fig. 1, the typical voltage and current traces at the power electrode located the height of 0, 0.25 H_L with PRF of 50 and 800 Hz for jet exit velocity of 7.9 m/s are illustrated in Fig .2. The duration of pulse voltage is approximately 100 μs in all cases, and the peak voltage is near 5 kV and 6 kV at PRF of 50 and 800 Hz respectively shown in Fig. 2(a). Since the negative electric field is generated by applying high voltage to the space between the electrode and flame base, seen as an open circuit, and the observed current curve can be regarded as the displacement current. Additionally, the presence of several micro-discharges during the voltage pulse is apparent to form the current bursts. Each individual burst has a very short pulsewidth of 100 ns with a peak current of 10 mA. Probably, each individual burst is related to a pulse corona discharge. This conjecture can be supported by the evidence that the current bursts appear more frequently on current curve, shown in Fig. 2(b). The red and blue lines symbolize the discharge voltage and current respectively. By comparison, the probability of pulsed-corona discharges occurred is much higher based on the implication for numerous current bursts.

It is well known that in non-premixed jet flame the flame edge will suddenly lift off from nozzle rim as the jet velocity increases, and stabilize at a downstream location favored for flame combustion, resulting in a lifted flame. However, hysteresis behavior can be found in the reattachment of a lifted jet flame which requires reducing the jet exit velocity below its original liftoff velocity. The photographs shown in Fig. 3 illustrate the effect of applying pulse high-voltage to the single electrode located at the height of 0 H_L on stabilization of lifted flames. The operated conditions are set to pulse repetition frequency of 800 Hz and jet exit velocity of 7.9 m/s. Evidently the lifted jet-flame is able to approach the power electrode alone by applying a fast-rise-time DC pulse of negative polarity and stabilize at the location upstream compared the natural case.

Fig. 4(a) depicts the enhancement stabilization in mean liftoff height with applying repetitive pulse high-voltage discharges for various cases of PRF's. The nature turbulent propane-jet diffusion flame, represented by PRF of 0 Hz, is lifted off as exit-velocity value increased to 7.9 m/s, and is reattached to the nozzle rim at jet exit velocity of 5 m/s. The mean liftoff heights can be effectively reduced by increasing the PRF from 100 to 800 Hz at the larger exit-velocity value than flame lift-off velocity for the electrode height of 0 H_L, and have a trend of linear increase in jet exit velocity. For the case of lower exit-velocity value it is possible that the flame anchor at nozzle rim with pulse discharges applied the higher PRF than 100 Hz. As a result, the hysteresis phenomenon can be avoided, that of favored flame stability. However, Fig. 4(b) shows the difference of enhanced stabilization by applying pulsed-discharges with a fixed PRF of 800 Hz among the various electrode heights of 0, 0.25 and 0.5 H_L. It seems that there are two different enhanced effects of electric discharge on the lifted flames. As the located height of electrode at 0.25 H_L, the mean liftoff heights increase slowly from jet exit velocity of 5 to 9 m/s, and are higher than those measured in the cases of 0 H_L. When exceeding exit-velocity value of 10 m/s, the flame stabilizes in the vicinity of powered electrode, located at 0.25 H_L and 0.5 H_L, and that result in the lower mean liftoff height than the case of 0 H_L. It is implied that the pulsed corona discharges may be generated by increasing the located height of powered electrode, and to enhance lifted flame stabilization.

4 Conclusion

The enhancement of turbulent lifted propane-jet flame stabilization by applying the repetitive high-voltage electric pulses to the single electrode placed various locations has been experimentally investigated through measuring the mean liftoff heights. The major results show that the mean liftoff height can be reduced more effectively by increasing the PRF of electric discharge from 100 to 800 Hz at the electrode-located height of 0 H_L in the liftoff regime of flames, and that the flame can be reattached to a nozzle in the hysteresis regime as applying PRF of 800 Hz. By contrast, the pulsed corona discharges are probably produced by moving powered electrode toward to instantaneous flame base, as a result, improving flame stabilization in terms of a monotonous variation in mean liftoff height with an increase in jet exit velocity.

5 Figures

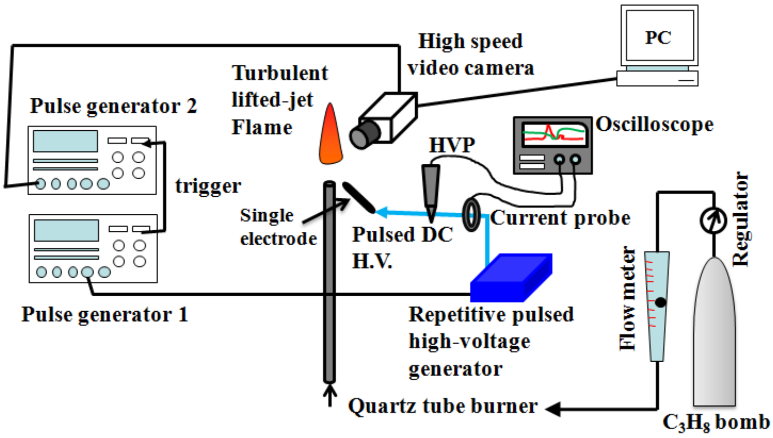

Figure 1. Schematic of experimental setup.

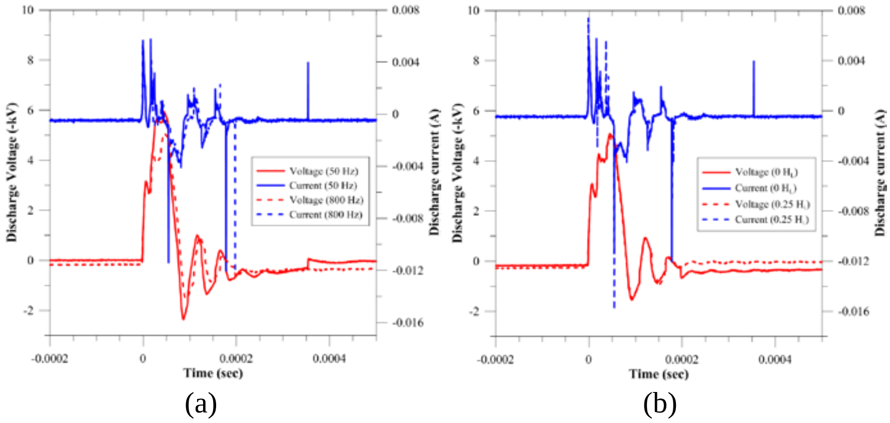

Figure 2. Typical voltage and current curve of pulsed-DC SECD showing several microdischarges. The pulse duration is 100 μs. Red lines represent discharge voltage, and blue lines represent discharge current. (a) for various PRFs at electrode located height of 0 H_L. (b) for various electrode located heights with PRF of 800 Hz.

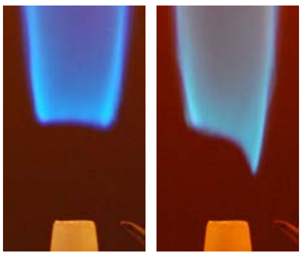

Figure 3. Photographs of lifted flames without (left) and with (right) pulsed discharges for jet exit velocity of 7.9 m/s and PRF of 800 Hz. The located height of electrode is 0 H_L. The lifted flame base with a cusp-like shape in the discharge case.

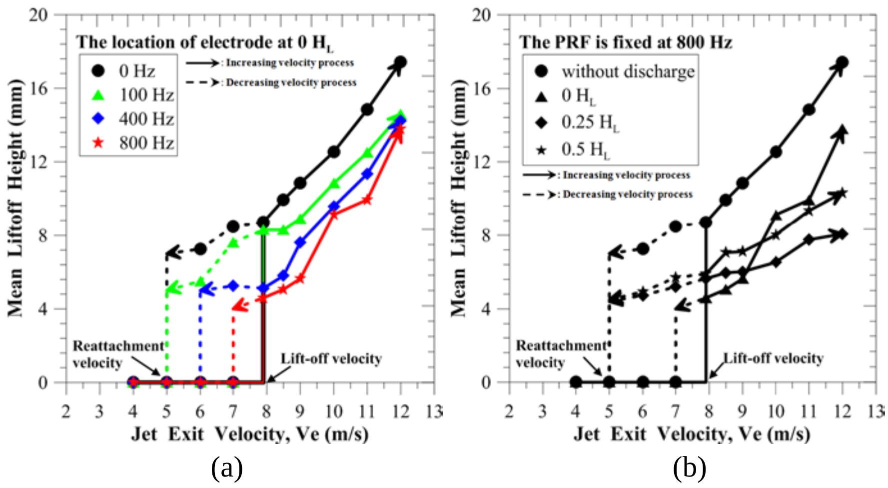

Figure 4. Mean liftoff height versus jet exit velocity for (a) various PRFs of 0,100, 400 and 800 Hz at the electrode-located height of 0 H_L. (b) various electrode-located heights of 0, 0.25 and 0.5 H_L with a PRF of 800 Hz.

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