Stabilization of Turbulent Lifted Jet Diffusion Flames Using Repetitive Pulsed-Arc Discharges

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1 Abstract

In the present study, the effects of repetitive pulsed-arc discharges on the stabilization characteristics of turbulent lifted propane jet diffusion flames are investigated through detailed experimental measurements. The investigations are conducted using non-intrusive diagnostics of shuttered laser Particle Image Velocimetry (PIV) and a High-speed digital camera to record the initiated flame kernel edges propagation sequences caused by pulsed-arc discharges to study the flame stabilization process. The results show that the averaged liftoff height is reduced significantly when applying high repetition rate of pulsed-arc discharges together with a low jet exit velocity, and the lifted jet flames in hysteresis region can even reattach to burner rim for the case of repetitive rate at 100 Hz. Furthermore, by analyzing the velocity streamlines and vorticity field profiles in the upstream of lifted flame base from PIV measurements, it is found that the turbulent vorticity intensity is significantly enhanced when pulsed-arc discharges are applied. Therefore, the probability of successful self-sustained flame kernel propagation is increased leading to enhanced flame stability.

Keywords: pulsed-arc discharges, ignition, flame stabilization, partially premixed flame

2 Introduction

The stabilization of lifted jet flames is an important issue for analyzing problems concerning the local ignition, flame propagation, extinction and re-ignition in numerous industrial applications. In the past, several investigations have been carried out to understand the stabilization mechanisms of lifted jet diffusion flames through detailed flow visualization study in the interaction of the flame with the flow structure [1, 2] and systematic experimental measurements of the flame structures at the lifted flame base using non-invasive laser diagnostic techniques [3-6]. These reports indicate that the stabilization process of turbulent lifted jet flames is a consequence of occurring alternatively between extinction and re-ignition events. Recently the concept of edge-flame and triple flame propagations that dominate the stabilization of turbulent lifted jet flame was also widely accepted [7, 8]. The critical

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conditions of stabilization of turbulent lifted-jet flames have shown that the mixture fraction is within the flammability limit [9] and the magnitude of local flow velocity is less than three times of laminar flame speed [10] at the instantaneous flame base. On the other hand, the ignition issue in inhomogeneous turbulent flow has been investigated due to take account of a random nature for igniting in turbulent non-premixed jets due to the variability in the mixture composition [11], which are also practically important for combustor performance such as gas turbine engines and spark internal engines. Therefore, the spark ignition in turbulent non-premixed lifted jet flames and subsequent edge flame propagation in inhomogeneous turbulent jets in still air is experimentally studied with various spark discharge parameters [12]. The results show the obtainment of a successful flame kernel in localized turbulent non-premixed jets must require the favorable conditions with low local velocities and low turbulent velocity fluctuations at the spark instant and location. In addition, the successful self-sustained flame propagation in turbulent mixing layers does not more easily appear through using an ignitor located at a fuel-lean mixture fraction region than at a fuel-rich and stoichiometric mixture region with the same input energy. When increasing the initial mixture fraction gradient at the spark gap located in the stoichiometric mixture, the propagation of flame front along the stoichiometric mixture fraction isosurface is also slow down. These phenomena are demonstrated by using three-dimensional compressible Direct Numerical Simulations (DNS) with simplified chemistry [13]. Consequently, the instantaneously local flow patterns and fuel mixture fraction profiles at the spark gap would determine the development of flame kernel initiated by electrical spark discharges, and the propagation of survival flame are modified by the rate of heat transfer from the flame surface to surrounding cold mixture due to turbulent convection and the rate of heat release from chemical reactions. Therefore, the spark location in turbulent mixing layers which below the lifted flame base would be a key point to control the stabilization of turbulent lifted jet flames. Moreover, the stability of turbulent lifted jet flames can be enhanced by using the repetitive pulsed high-voltage discharges generating the non-equilibrium plasma [14]. The cold radicals created through the ultrashort-pulse (10 ns) discharges with high repetitive rate (200 Hz – 15 KHz) are used to enhance the chemical reaction rate and decrease the liftoff height of turbulent lifted jet flames effectively [15]. By contrast, the repetitive rates of pulsed equilibrium plasma discharges such as pulsed-arc discharges relative to pulsed non-equilibrium discharges is lower, but the current density provided by the pulsed equilibrium plasma is closed to that of pulsed non-equilibrium plasma. As a result, the propagation of flame kernels would be affected by the hot gas volume provided through repetitive pulsed-arc discharges with the high-current density.

It is more difficult to ignite a lifted flame, which has high local strain rates or scalar dissipation rates appear in the upstream mixing layer and the effects of the repetitive pulsed-arc discharges on the stabilization of turbulent lifted jet flame is not well known. Therefore, in the present study, the effects of repetitive pulsed-arc discharges on the stabilization characteristics of turbulent lifted propane jet flames are investigated through detailed experimental measurements.

3 Experimental Methods

In order to investigate the effects of repetitive pulsed-arc discharges on the stabilization of turbulent, lifted jet diffusion flames, the schematic diagram of experimental setup used is shown in Fig. 1. It consists of a quartz-tube burner with a fuel supplied system for generating the turbulent lifted jet flame, a repetitive pulsed-arc discharge system for creating the high inverse-inductive-potential electrical spark discharges between two pointed electrodes made of stainless-steel with a diameter of 1 mm, a shuttered particle image velocimetry (PIV) system for measuring instantaneous velocity at flame base of turbulent lifted jet flames, and a high-speed charge-coupled device (CCD) camera for recording the instantaneous images of turbulent lifted flame base. The flow rate of fuel stream provided from a liquid propane cylinder with a regulator can be controlled by a well-calibrated floating flowmeter. 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 range of jet Reynolds number of operating condition is approximately 5200 – 7800. The main features of repetitive electrical discharges are energy deposited of single pulsed discharge and pulsed-arc duration near about 200 mJ and 300 μs respectively. The repetitive rates of the pulsed-arc discharges are controlled at 10, 50, and 100 Hz by using a pulsed generator with a switched electric circuit. The electrodes with a constant gap width of 10 mm are placed at the height of 0.25 H_L located above the jet exit and fixed at the radial location nearby jet mixing layer in the upstream of lifted flame base, where H_L is the mean liftoff height of various exit velocities in the cases without discharges. The images of instantaneous lifted flame base are obtained by using the synchronized triggering high-speed digital camera (PCO1200HS) with 2 ms exposure time, and the mean liftoff heights are measured by digital image processing from sampling time of 1 s for all cases. The shuttered PIV system includes two pulsed Nd:YAG laser, a high-resolution CCD camera (SharpVision 1300DE) with double-exposure function interlaced a mechanism shutter, and an TiO_2-particle seeding system. The CCD camera system, two laser pulses, and pulsed arc-discharge are synchronized with a digital delay pulsed generator. The PIV measurements will benefit to explain the flame reattachment phenomenon.

4 Results and Discussion

The liftoff and blowout stability phenomena of a jet diffusion flame can be observed by increasing the jet exit velocity, and the hysteresis behavior is found in the reattachment process when the jet exit velocity is reduced below its original liftoff velocity. Two major parameters considered in the present study are the location of electrode pairs in the mixing layer of free fuel-jet flow and the repetitive rate of pulsed-discharge. The instantaneous liftoff height of turbulent lifted jet flames is defined as the distance between the burner exit and the most upstream position of lifted flame base. The averaged liftoff heights versus the jet exit velocity for different repetitive rates as the electrode location of 0.25 H_L are depicted in Fig. 2. In this figure, the solid lines represent the evolution of liftoff height by increasing the exit velocity to liftoff velocity from the attached situation, while the dashed lines illustrate the hysteresis phenomena when decreasing the exit velocity to reattachment velocity from the lifting situation. Apparently, the averaged liftoff height can be greatly reduced in the present of higher repetitive rates of pulsed-discharge and slightly increased in the case of low repetitive rate. The unusual liftoff height for 10 Hz case may be suggested that the vortices generated by the simultaneous pulsed-discharges at the upstream of lifted flame base would perturb the instantaneous liftoff height. It is particularly interesting to note that the lifted flame base can even be reattached to the tube rim as jet exit velocity is reduced to less than 9 m/s for repetitive rate at 100 Hz. In the case of repetitive rate at 100 Hz, the previously reattached flame caused by pulsed-arc discharges is able to persistently anchor to the tube rim while the arc-discharges cease for jet exit velocity of 8.6 m/s. The photographs in Fig. 3 show the phenomenon described above.

In order to understand the detailed sequence of flame-kernel edges propagation with various repetitive rates of pulsed-arc discharges, the instantaneous heights of initiated flame kernel endpoints by arc-discharges and lifted flame base are recorded by using high-speed CCD camera operated at 1000 fps. Fig. 4 delineates the sequential trace of lifted flame bases and the flame kernel edges propagating from the discharge location of 0.25 H_L to the downstream lifted flame base for successful flame reattachment phenomena as using repetitive discharge rate of 100 Hz. The instantaneous height for the up-edge of flame kernel increases with time variation and eventually the edges are combined with the lifted flame base. The down-edges of flame kernels can be propagated to upstream location close to tube exit, and the residence time is sufficient for flame kernel stabilization at the location below the electrode pairs until the next pulsed-discharge as shown by the star symbols in Fig. 4. The heat released rate and reaction rate of flame kernels may be electrically augmented up to flame reattachment by continuous supplying pulsed-arc streamers with very high-energy concentration beyond the reaction front of flame-edge. Oppositely, in the case of repetitive rate at 10 Hz, the down-edges of flame kernel propagate to the downstream location and merged with original lifted flame while the pulsed-discharges repeat. Therefore, the influence of pulsed-arc streamer on lifted flame base is insignificant.

In this work, by using the mechanical shutter to control the exposure time of the two PIV images in sequence, the flame-edge boundary can be identified clearly in the second image of the PIV image pair. Based on above method, the contour of luminous flame region can be superimposed on the PIV velocity streamlines and the vorticity field profiles. Fig. 5 shows that the instantaneous velocity streamlines and vorticity field profiles overlaid with the contours of propagating flame-kernel and instantaneous lifted flame base measured from the location of instantaneous lifted flame base to pulsed-arc for successful flame-kernel initiated case. Apparently in Fig. 5(a), the vortical fluid motion appear frequently in the region of initiated flame-kernel edges to instantaneous lifted flame base, and the presence of vortical structures around the flame kernels also can be seen in Fig. 5(b), indicating that the significant mixing of fuel and air is caused by pulsed-arc discharges.

5 Conclusion

The effects of repetitive pulsed-arc discharges on the stabilization of turbulent lifted jet diffusion flames are experimentally investigated. Results show that the stability of a lifted propane-jet flame can be enhanced, and the liftoff height of turbulent lifted jet flames is significantly decreased by applying high repetitive rate of pulsed-discharges at the location of electrodes at 0.25 H_L. In particular, the flame reattachment phenomenon can be sustained with repeatable pulsed-arc discharges in the case of high repetitive rate at 100 Hz, and the reattachment condition is not disappeared after the pulsed-arc discharges cease. When the flame kernel down-edge propagates to upstream location close to jet exit, the continuous pulsed-arc streamers as using the high repetitive discharge rate may electrically augment the heat release rate and reaction rate of the reaction front of edge flames result in flame reattachment occurred. The instantaneous velocity streamlines and votricity field in the upstream of lifted flame base are measured in order to explain the onset process of flame reattachment phenomena. The result shows that considerable vortical structures exit in the flow field of initiated flame kernels by pulsed arc-discharges.

6 Figures

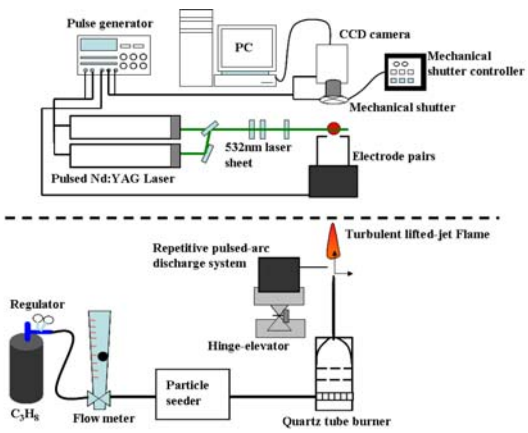


Figure 1. Schematic diagram of the experimental setup.

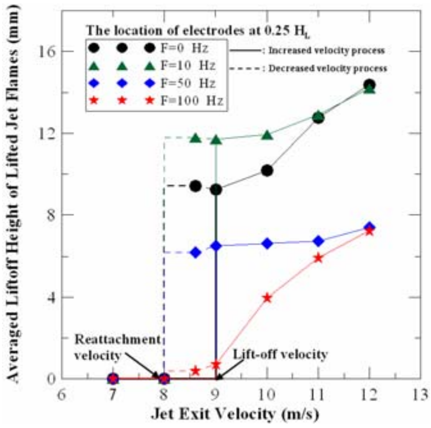
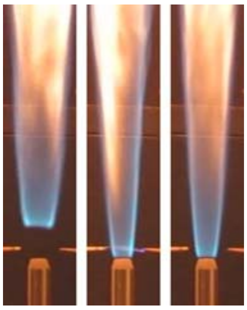


Figure 2. Averaged liftoff height versus jet exit velocity for different repetitive rates as the electrode location of 0.25 H_L, dashed lines: hysteresis region, solid lines: liftoff region.



(a) (b) (c)

Figure 3. Observation of repetitive pulsed-arc-enhanced flame reattachment phenomena for jet exit velocity of 8.6 m/s. (a) Without discharge. (b) With discharge. (c) Discharge ceased.

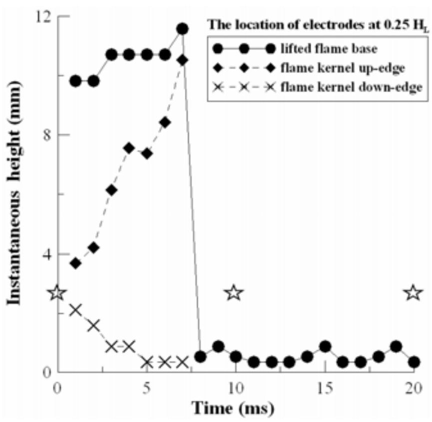


Figure 4. The sequential instantaneously location of lifted flame bases and the flame-kernel edges propagating from the discharge location of 0.25 H_L to the downstream lifted flame base and to the upstream tube exit as using repetitive discharge rate of 100 Hz for jet exit velocity of 8.6 m/s, star symbols represent the pulsed-arc discharges for repetitive rate at 100 Hz.

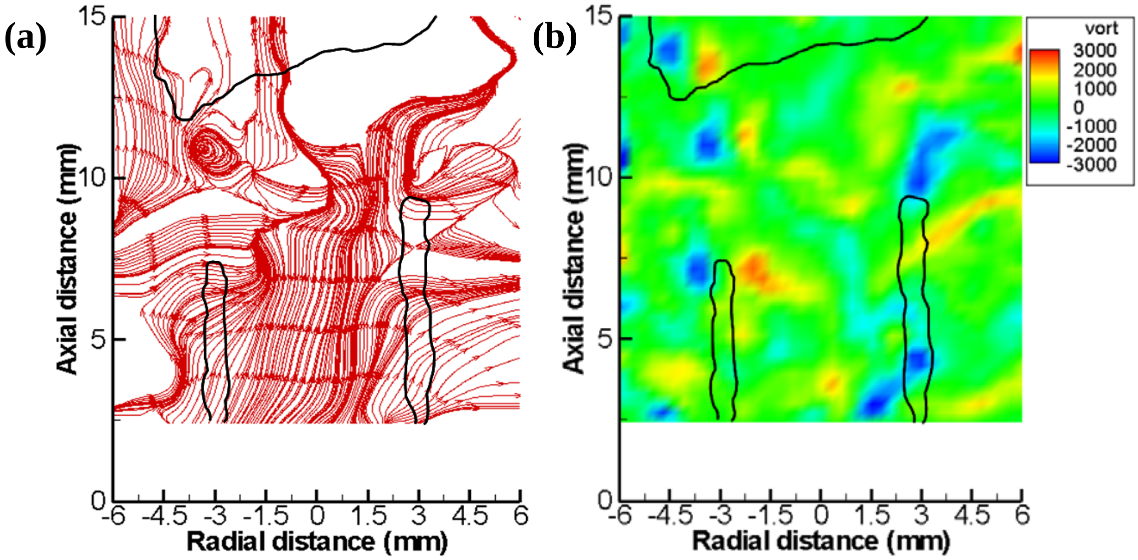


Figure 5. The flow-field of a successful flame-kernel initiated by pulsed-arc discharge with the contours of flame kernels and lifted flame base measured by PIV. (a) Instantaneous velocity streamlines profile. (b) Vorticity field profile.

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