[1]High speed Diagnostics of Blow out precursors in a plate stabilized flame

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Abstract

High speed diagnostics are used to study the process of blow out of a V-flame stabilized on a thin straight metal plate. This work uses high speed PIV, high speed chemiluminescence and high speed Schlieren imaging to understand the flow-flame dynamics during the loss of stabilization in plate lip stabilized flame. The local flame liftoff during a precursor event occurs due to velocity perturbations from the upstream, and when the flame moves away from the plate, the flow field tends towards cold flow which has lower velocity near the plate, providing the flame a path to come back to the plate. It was also observed that the time duration and movement of flame are random. The shape of the flame front was found to be related to the fuel type used.

Introduction

Combustors are designed to withstand high velocities while operating at its optimum condition with low emission. Operations in premixed lean conditions offers low NOx emissions but can have blowout of the combustor, as the flame cannot sustain itself against incoming perturbations. Nowadays, several combustion researchers try to understand the response of flame to incoming perturbation. While there are many stabilization mechanisms used for flame holding, this paper will focus on the simplest flame holding mechanism, plate lip stabilized flame. The focus will be on understanding the process of blowout and the occurrence of precursor events prior to it.

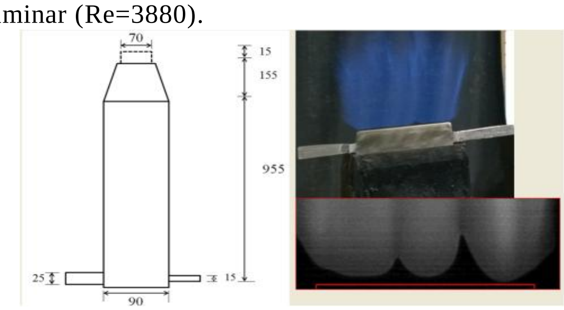
Wrinkling of flame front due to jet shear vortex was observed by Durox et al. [1]. Precursor study of flame was done by Sachan et al. [2]. They found out that there is a local lift off followed by reattachment of the flame during the process of stabilization loss. Dynamics of burning velocity response to harmonic velocity disturbances was observed by preetham et al. [3]. The effect of flame curvature on the propagation and structure of premixed flame was done by Choi et al. [4]. The response of laminar flame to equivalence ratio perturbations was studied by Cho et al.[5].

Blow out characteristics of conical flame under the influence of upstream velocity fluctuation was analyzed by Andres et al. [6]. The anchoring mechanism of bluff body stabilized flame was observed by Kedia et al. [7]. Temperature distribution over an axisymmetric 2D Bunsen flame under the influence of preferential diffusion and aerodynamic stretch was studied by Law et al. [8]. Effect of radius of curvature on flame during blow out was studied by Kawamura et al. [9]. Stabilization of inverted flame without the influence of heat loss was observed by Sung et al. [10]. Interaction of adjacent flame surface was experimentally analyzed by Yokomosi et al. [11].

Current understanding of the lean blowout of combustors is that there are random on-off events that occur just prior to blowout of the combustor, known as precursors to blowout. This study focuses on understanding the cause and the behavior of the precursor events prior to blowout of a plate stabilized flame ('V-flame'). This work attempts to understand the dynamics of flow-flame interaction near blowout. High speed chemiluminescence, high speed Schlieren and high speed PIV are used for understanding the flame behavior during the loss of stabilization. The present work also helps to understand the effect of incoming perturbations on flame near lean conditions.

Experimental Setup

Figure 1 shows 2D rectangular burner with a flat plate tapered at the end. Experimental setup consist of a 2D rectangular burner having a cross sectional area of 80*20 mm^2 , a flat plate of 70 mm length, 32 mm width and 2mm thickness with tapered end is provided at the exit of the burner. The plate is tapered so as to reduce the amount of heat transfer from flame to plate. Fuel and air flow rates are monitored by mass flow meters. Ignition is provided at the top of the plate. Flame appears as a 'V'flame stabilized over the plate tip. Experiments are done by keeping airflow rate as constant and fuel flow rate varying slowly, in order to change the fuel-to-air ratio. Experiments were conducted for two different fuels, viz., CH_4 and Liquefied Petroleum Gas (LPG) - a mixture of butane(60%) and propane(40%). Burner is designed in such a way that the flow coming from the exit is laminar (Re=3880).



(a) (b)

Figure1. (a)Schematic of the burner setup, and (b) (top) flame stabilized at the end of the plate tip, (bottom) Chemiluminescence image of the flame near blowout.

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Proceedings of the European Combustion Meeting 2015

IDT-N4 and Photron camera were used for capturing images at high frame rates for Schlieren, chemiluminescence and PIV experiments. A Litron double pulsed Nd-YLF high speed laser is used for the PIV measurements. The PIV data was obtained at 1mm to the side of the plate, so as to observe the velocity field upstream of the plate during the blowout process. There were also cases when the PIV data was obtained perpendicular to the plate.

Results And Discussion

Results are presented in the form of PIV data, and Schlieren and chemiluminescence images. Flame is stabilized by the jet at the bottom. Figure 2 shows the gray scale images of flame during the loss of stabilization. The images were recorded at 300 fps. High speed chemiluminescence movies show that as blowout is approached, the flame temporarily lifts off from the lip of the plate at some locations along the length of the plate. The LPG flame front has a different shape near the lip compared to that of CH_4. This could be explained based on the differential and preferential diffusion of species in respective cases[8].

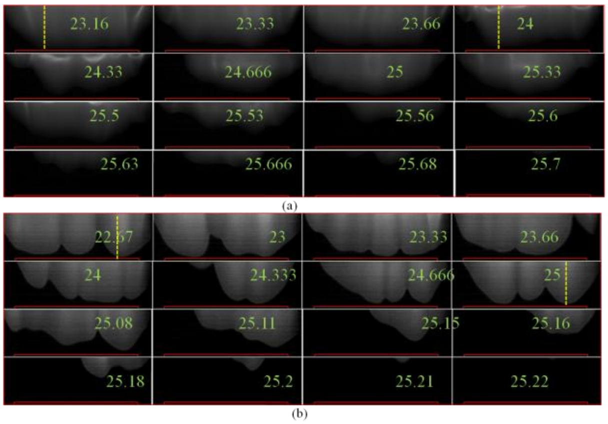

Figure 2. Chemiluminescence gray scale images of the flame during the blowout process for (a) LPG and (b) CH4, recorded at 300 fps. The numbers superscribed on the images are time[s].

In lean conditions, Le >1 for LPG and Le < 1 for CH4. Both the flames have a front that is a combination of 'V' and inverted 'V' shapes. However, one can see distinct differences in the inverted 'V' parts of these two flames, viz., the LPG has shallow curves while the CH4 flame has sharp kinks. This is because differential and preferential diffusion processes of species favors increase in flame speed for LPG flame, while it decreases the flame speed for CH4 flame.

In experiments, fuel to air ratio (equivalence ratio) is a major parameter that determines the ability of the flame to sustain incoming perturbations Near lean blowout, there are random on-off events that occur just prior to blowout known as precursors to blowout. In figure 2(a), at time 23.16s, there is a dashed line marked on the image to point to one such precursor event. At this location, the flame partially lifts off from the plate lip and after some time (24s) reattaches to the lip. From time 24.33s onwards, the flame gradually leaves the plate tip and never returns back to the plate tip and at 25.7s there is no flame near the plate, completing the blowout process. Figure 2(b) shows similar precursor event, from 22.67s to 25s, and blowout process from 25.08 to 25.22s.

Figure 3 shows chemiluminescence images and simultaneous velocity data as colour coded PIV quiver plots, at high lean equivalence ratios. Highest velocity is shown as white and the lowest is green and blue. The chemiluminescence images show that the flame is attached to the plate lip the whole duration shown. This confirms that there are no precursor events during this time. The PIV data shows that there are white patches in the upstream of the lip, showing that there are high velocity patches in the upstream of the flame, approaching the flame. However, the chemiluminescence images show that the flame holds onto the plate lip when the high velocity flow packets reach the flame. Figure 4 shows a plot of time variation of the flame standoff distance and the velocity upstream of the lip. This is intended to compare the 2D data shown in figure 3 in a easier form, but at one location.

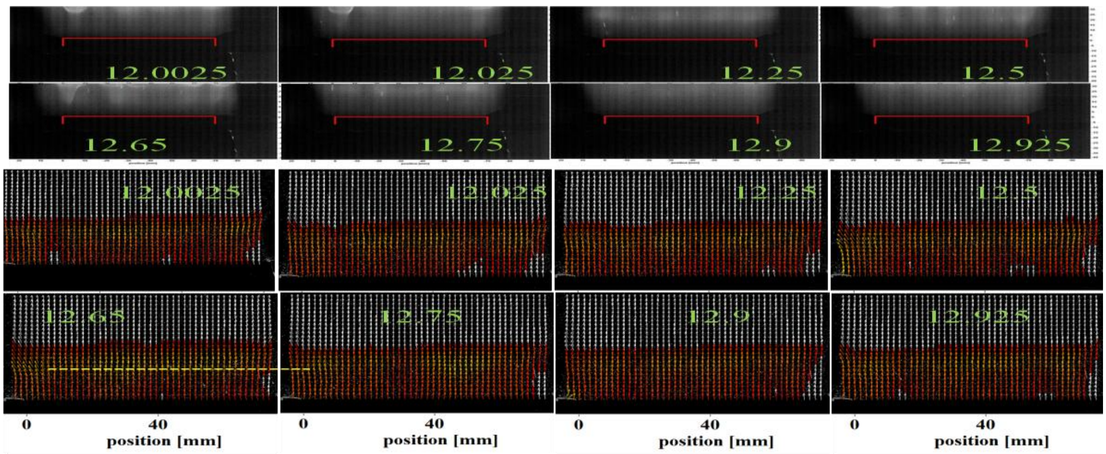

Figure 3. Chemiluminescence image sequence(a) of CH4 flame, and (b) PIV data, when the flame is away from blowout conditions. Both data were recorded at 400 fps. The horizontal line in the PIV data shows the location of the plate lip. The vertical dashed line shows the location for the data in figure 4.

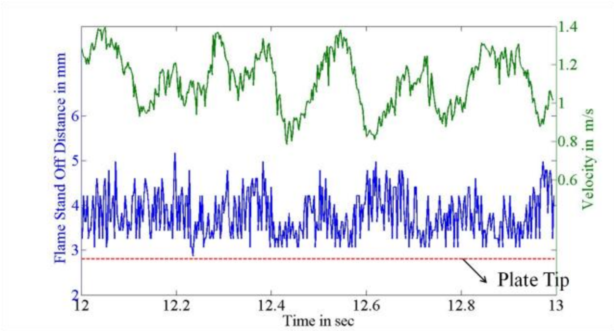

Figure 4. Time variation of flame standoff distance and spatial averaged velocity, at a fixed location (55mm from left end of plate, shown in figure 3), as a function of time, for stable CH4 flame.

Figure 4 shows the time variation of flame standoff distance at a fixed location, and the velocity upstream of it. It is evident that there are velocity fluctuations in the upstream of the flame, and it is not periodic but appears to be random. The flame moves less than 1mm, due to these incoming perturbations. Thus the flame is strong enough to withstand the random incoming perturbations, at high equivalence ratios.

Figure 5 shows chemiluminescence images and simultaneous velocity data as color coded PIV quiver plots, close to blowout. The chemiluminescence images show that the flame is detached from the lip at some locations along the plate lip. The PIV data shows that there are white patches in the upstream of the lip, showing that there are high velocity patches in the upstream of the flame, approaching the flame, similar to those shown in figure 3. The vertical line in the chemiluminescence image shows the location of one 'on-off' event occurring during this sequence of images. The flame is holding onto the plate lip in the first image, and progressively lifts off from the lip at the specified location till the end of the image sequence. During this time one can notice that there is a high velocity near that specified location.

Figure 6 shows a plot of time variation of the flame standoff distance and the velocity upstream of the lip. This is intended to compare the 2D data shown in figure 5 in a easier form, but at one location. Firstly, one should notice that the flame is not very close to the plate lip, since the equivalence ratio is close to blowout, and the flame is weaker. The flame is only around 7mm away from the lip as compared to around 3mm in figure 4.

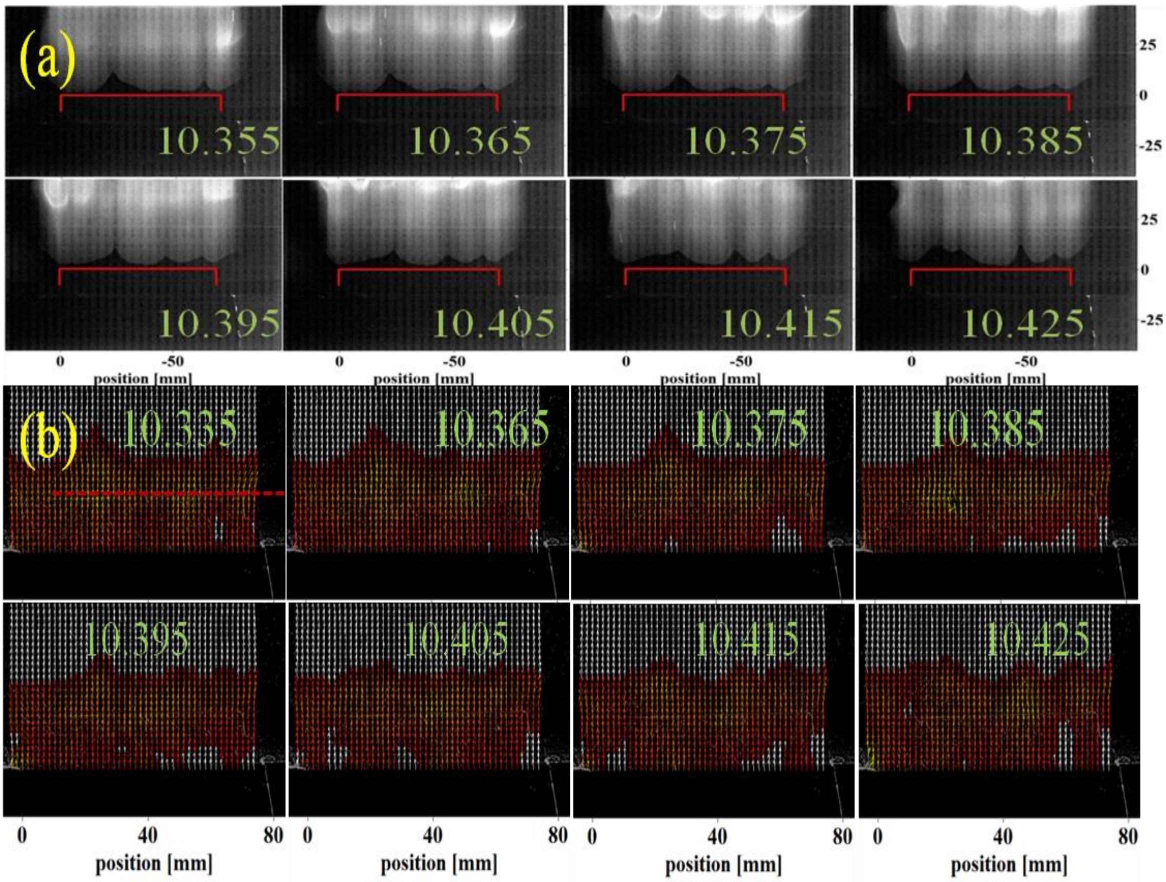

Figure 5. Chemiluminescence image sequence(a) of CH4 flame, and (b) PIV data, when there are precursor events. Both data were recorded at 400 fps. The horizontal line in the PIV data shows the location of the plate lip. The vertical dashed line shows the location for the data in figure 6.

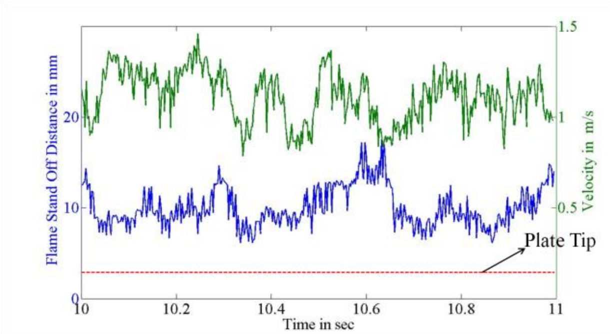

Figure 6. Time variation of flame standoff distance and spatial averaged velocity, at fixed location (50mm from left end of plate, see figure 5), as a function of time, for CH4 flame near blowout.

The velocity fluctuations in figure 6 are near the same order as that shown in figure 4. The figure also shows that the flame leaves the lip at the specified location and moves downstream several times, following which it moves upstream to go as close as 7mm from the lip. As velocity increases above the average velocity of 1.04 m/s, the local flame moves away from the plate tip after some time delay. The flame moves upstream when the velocity drops below 1m/s. This again has a delay which appears to be a slower response to the velocity variations. This shows that flame is more sensitive to incoming perturbation when burner is operating at lean conditions.

The average delay for the flame to start moving up after the velocity increases above 1.04m/s is found to be 15ms. This delay is of the order of the timescale for the flow to move from the point of velocity measurement to the plate lip. Similar average delay for reattachment after the velocity goes below 1.04m/s was found to be around 30ms. This number is significantly higher for two reasons: 1) the flame standoff distance is higher, and 2) the flame is propagating against the flow and thus is moving slower. Thus it can concluded that the flame lift off from the lip occurs when there is a high velocity perturbation approaching the flame, and the flame is weaker to sustain itself against it.

Figure 7 shows side view chemiluminescence and PIV data of CH4. The chemiluminescence camera was focused in the same plane as that of the PIV data. However, the focal plane thickness was around 30mm. Thus there will be multiple flame surfaces seen in each of the chemiluminescence images, when the flame has different standoff distances in this thickness. To simplify the effort for the reader, the flame tip of the precursor is being pointed out in the side view by arrows.

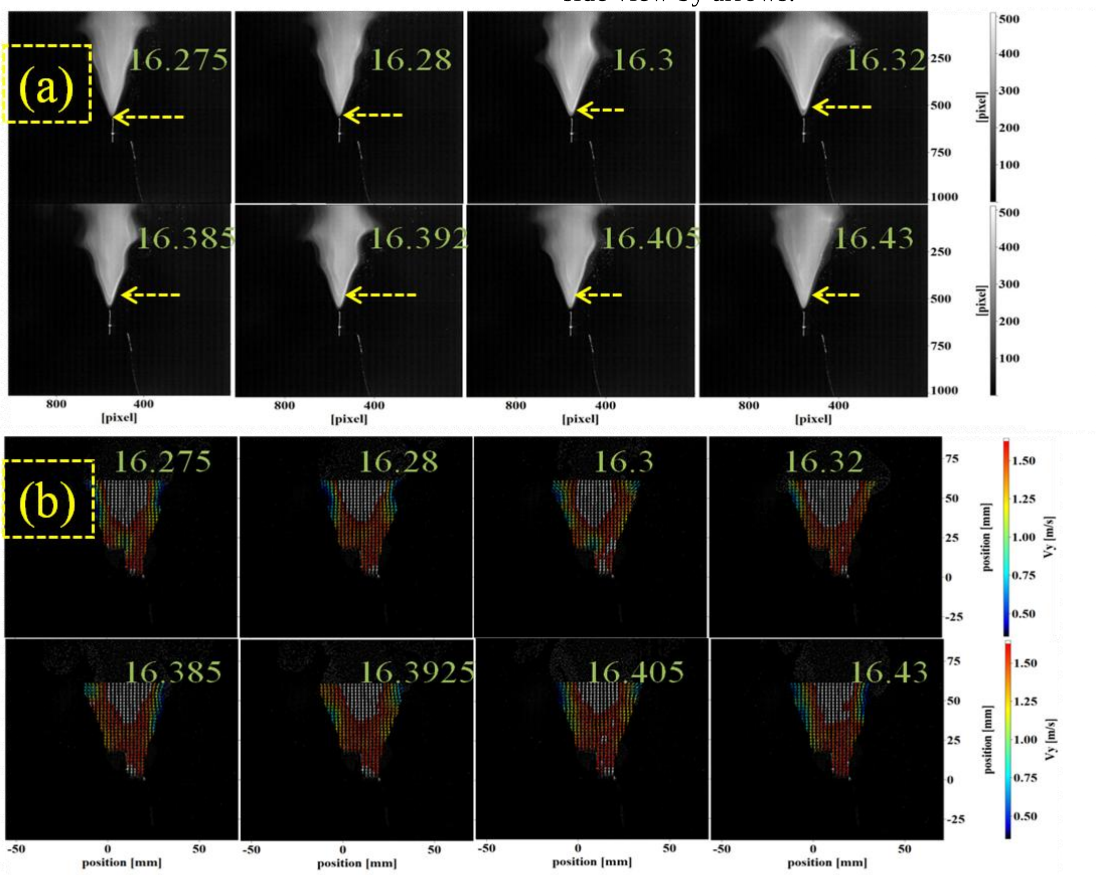

Figure 7. Sequence of simultaneous chemiluminescence images(a) and PIV data(b) of side view of CH4 flame having a precursor event. Both data were recorded at 400 fps. The flame tip in the PIV plane is pointed out in the chemiluminescence images by arrows.

From figure 7, it is seen that when flame is moving up, there is white patch in the PIV quiver plot, indicating high velocity upstream of the plate. Thus this data also agrees with the conclusions from the previous figures that the flame moves up from the lip due to incoming velocity perturbations.

Figure 8 shows high speed chemiluminescence images and simultaneous high speed Schlieren (vertical knife edge) images of CH4 flame. The Schlieren imaging along the side view of the plate and is focused in the mid length plane of the plate. However, the focal plane thickness here will be around 30mm again. Thus the Schlieren images are sensing horizontal density gradients that occur in the region of mid 30mm length of the plate, as seen from side view. The vertical dashed line in the chemi-luminescence image shows the location of flame moving back in this sequence of images. This is the region of interest for this discussion.

At time 9.98s, Schlieren image shows a shear layer growth (see arrow) on the side of the plate, and it is growing until 10.04s. This appears to be boundary layer separation from the hot plate, causing mild density gradient to be seen in Schlieren images. This shear layer growth decreases the velocity upstream helping flame to move towards the plate. These observations suggest that the flame is moving back to the tip when there is a shear layer growth on the sides of the plate.

Figure 9 shows Schlieren and chemiluminescence images of CH4 flame during the blow out condition. It is to be noted that the sequence of images is part of the same run as the sequences shown in figure 8. The flame lifts off from several locations along the plate tip and eventually most of the flame is far away from the lip. There are very few 'fingers' of the flame holding onto the lip, which progressively leave the lip, causing blowout. It was also observed in PIV data (not presented here) that the flame is moved out from the plate due to velocity perturbations. It is interesting to note that there appears the shear layer separation from the plate after the flame has left the plate. This suggests that the flow has a shear layer separation in cold conditions. This suggests that during a precursor, the local flow field has a shear layer separation that is akin to the cold flow field.

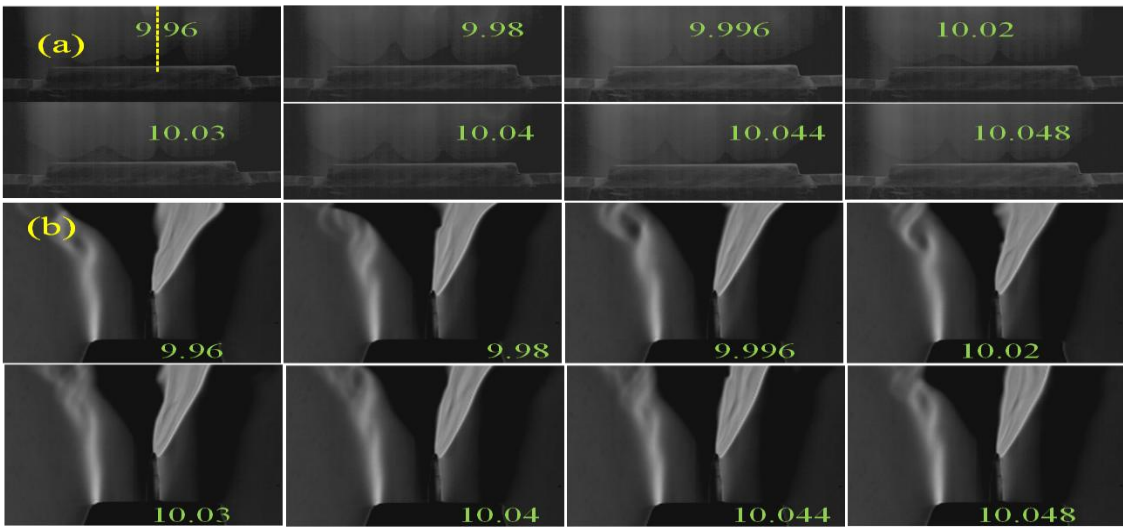

Figure 8. Image sequences showing CH4 flame having a reattachment event during a precursor. (a) chemiluminescence images, and (b) Schlieren images with vertical knife edge. Both sequences were recorded at 500 fps.

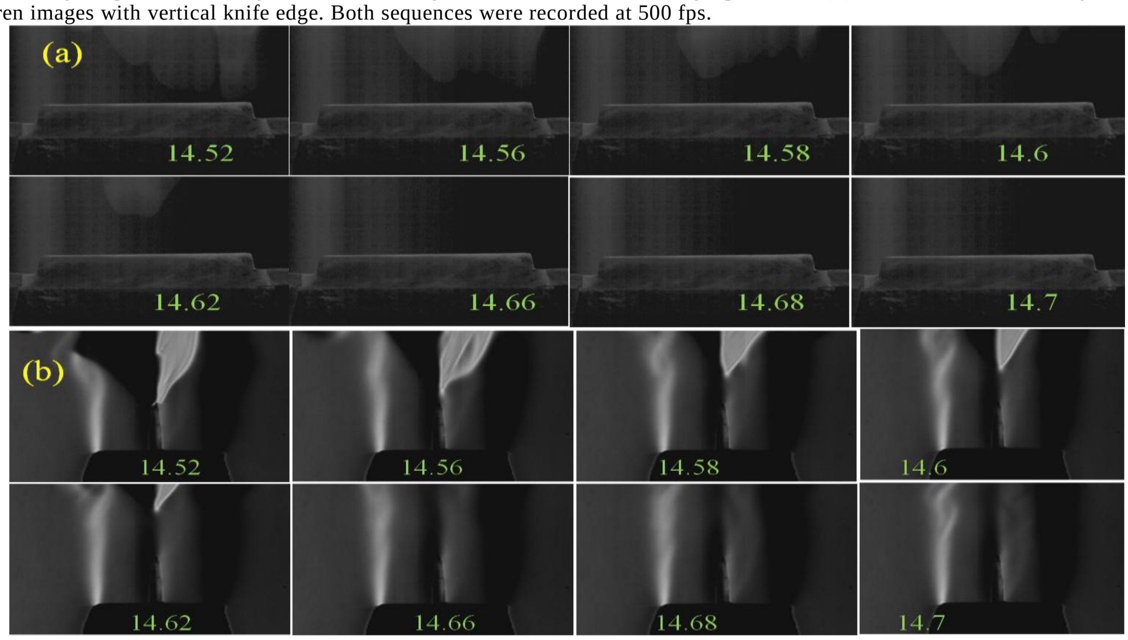

Figure 9. Image sequences showing CH4 flame blowout event. (a) chemiluminescence images, and (b) Schlieren images with vertical knife edge. Both sequences were recorded at 500 fps.

Conclusion

Shear layer stabilized flame from a straight, thin, metal plate with CH4 and LPG flames was analyzed near blowout conditions. High speed PIV and Schlieren imaging was used along with simultaneous high speed chemiluminescence imaging to monitor the flow field, and density field along with flame dynamics. The temporary flame lift off from the tip and its reattachment during the precursors to blowout and the full blowout process were studied in detail. It was also observed that the time duration and the extent of lift off from the lip were random, while on average they both increased as the blowout limit was approached.

The flame lift off was found to be due to high velocity perturbations pushing the flame tip downstream. It was observed that the perturbations exist always in the flow and the flame is sensitive to them only when the equivalence ratio is very lean. The nearby flames on either sides of this location are still stabilized and thus the overall flame is not lost. The flame surface front has different shapes depending on the fuel as dictated by diffusion of various species and heat.

The high velocity packets are short lived and the flame returns to the lip when the velocity decreases. It was found that the local flow field around the plate appears to be reverting to cold flow conditions with separated shear layer, when the local flame lift off occurs. This separation causes low velocity region helping the flame to move upstream. When the equivalence ratio is low, there comes a time when the flame leaves all of the lip length and thus blows out.

To summaries, the local flame liftoff during a precursor event occurs due to velocity perturbations from the upstream, and when the flame moves away from the plate, the flow field tends towards cold flow which has lower velocity near the plate, providing the flame a path to come back to the plate.

This work explains the occurrence of the precursor events and blowout process in a 'V' flame stabilized on a straight thin metal plate. Further efforts are underway to understand the effect of plate material, shape and thickness.

Acknowledgment

This work was supported by the Department of Science and Technology, Department of Aerospace engineering.,NCCRD

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