CHARACTERIZATION OF EXTINCTION EVENTS NEAR BLOWOUT IN SWIRL-DUMP COMBUSTORS

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This work examines the evolution of the lean blowout (LBO) process in a swirl-dump-stabilized combustor with center body. Previous studies identified extinction-reignition events as precursors to LBO. These events are investigated in greater detail using simultaneous fiber optic-based chemiluminescence sensors and high speed imaging in an atmospheric pressure, premixed methane-air combustor. It is found that the flame, which is stabilized above the center body, at first partially detaches due to turbulent fluctuations. This detached region moves around the center body due to the swirl and the feedback mechanism of the inner recirculation zone. As the LBO limit is approached, the weaker flame detaches more often and over a larger extent of the center body. When the flame is detached beyond a certain extent, enough cold packets of unburned gases move around the inner recirculation zone to reduce the feedback needed for stabilization and the flame detaches completely from the center body. This is the source of the extinction events previously noted in the sensor data. The flow field responds to the decreased heat release with a larger recirculation zone and stronger swirl. The flame shape and flame stabilization change to a tornado mode. In this mode, the flame is stabilized much farther downstream of the combustor inlet, but an occasional packet of burning gases is convected back to the inlet. If this flame packet is sufficiently strong, the original flow field and flame shape are restored. This return of the original stable flame mode is the onset of the reignition events found in the sensor data. Several occurrences of these events in time gradually weaken the combustion process and eventually the convected flame packets are not strong enough to restabilize the combustor, i.e., the combustor blows out. This understanding of the process of flame stabilization loss provides the necessary insight for improved design and analysis of LBO sensors systems.

I. Introduction

Efforts to improve power and propulsion systems have increasingly shifted to satisfy stringent emission standards. Changes to provide cleaner, more environmentally friendly energy conversion must be balanced by operability issues, however. Lean premixed combustion is a popular option to achieve lower emissions. For example, premixed natural gas combustors have demonstrated the ability to greatly reduce NOx emissions in ground power generation, and similar improvements are available for premixed, prevaporized liquid-fueled combustors. Even for current aeroengine combustors, which operate in a partially premixed mode with rapid mixing after fuel injection, increased fuel-lean operation may reduce NOx emissions. In both premixed and partially premixed combustors, however, the risk of flame blowout increases as the mixture is made leaner, as the weaker combustion process is more vulnerable to small perturbations in combustor operating conditions. [1]

Lean blowout (LBO) poses a problem in both steady and transient situations, e.g., when rapid power changes are required, for both aircraft and land-based turbine engines. Lean blowout in an aircraft engine poses a significant safety hazard, for example during power reductions involved in approach and landing. In land based engines used for power generation, blowouts require an expensive shut down and relight procedure, in addition to loss of power during this period. Currently stable performance is ensured by operating the combustor with a wide safety margin above the uncertain LBO limit (e.g., higher equivalence ratio). Thus for an engine designer, the challenge is to develop a combustor that achieves stable operation and low NO$_x$ emissions over the full range of engine conditions.

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Thus, the combustor designer must build enough margin into the design to prevent LBO at the worst case operating condition. Consequently, there can be an increase in NO_x production compared to what could be optimally achieved at other operating conditions. Enhanced performance will require a reduction of this LBO margin. This can be achieved by sensing proximity to LBO and using that parameter in a combustor control system.

Temporary extinction re-ignition events have been identified, from both chemiluminescence and acoustic radiation from the combustor, as precursors to LBO and their rate of occurrence has been used to sense the proximity to LBO.[2,3] A control system based on sensing these precursors was used to avoid blowout by active control of fuel distribution in the combustor.[4,5] From a sensing viewpoint, improved understanding of the dynamic processes that lead to loss of stabilization in swirl combustors will lead to improved data analysis for determining blowout proximity from LBO sensors and better placement of these detectors in a combustor to identify flame stabilization loss. In addition, it can also lead to methods to improve combustor stability, including passive methods (e.g., combustor design) and active methods (controllable actuators). Our previous work[6] was a first step toward better understanding of the dynamics of LBO precursor events and the physics that control their characteristics. This work is a more detail study of the physics and an attempt to explain the previous observations of blowout dynamics from a physical perspective.

II. Background

Combustor blowout is a complex problem involving the coupling of chemical reactions, heat transfer and turbulent fluid dynamics and has been a challenge in the research community for more than sixty years. There is a large body of work focused on understanding the mechanisms of flame stabilizations in high velocity streams. The stabilization mechanisms used to hold flames in high velocity flows are based on varying several parameters such as flow rate, flow geometry, swirl, heat release rates, fuel/air composition, and temperature.[7-16] Most of these efforts have focused on understanding the stabilization mechanisms and improving them; little attention has been given to understanding the dynamics of loss of stabilization.

There have been studies to understand the actual cause of extinction of simple flames. Several researchers have studied the cause of extinction in stagnation plane flames and concluded that strain rate is an important cause.[17,18] Strain rate can affect the rate of transport of species and heat, and thus has an influence on chemistry. There is evidence that local extinction of the flame is related to the magnitude and the rate of change of the local instantaneous strain rate.[19] Turbulent counterflow flames can even exist past the extinction strain rate for short duration depending on its history of strain.[20,21] It was found that the flame weakened gradually with periodic forcing of the flame, and thus extinction occurred after several cycles of forcing. Although these studies give insight into the physics of local flame extinction, there is not much work on understanding of the blowout of a combustor, which is more close to practical combustion systems.

Gas turbine combustors commonly employ swirl and sudden expansion to stabilize the flame. The presence of sufficient swirl causes a toroidal vortex structure to form in the middle of the combustor (denoted here as the inner recirculation zone, IRZ). There is in addition an outer recirculation zone (ORZ) created by the sudden expansion. The presence of the swirl-induced vortex core is suppressed by combustion and the sudden expansion, which makes the inner recirculation zone (IRZ) smaller for the case with combustion.[22,23] It is also observed that the turbulence characteristics are affected by the combustion process. The turbulent kinetic energy and the velocity fluctuations are increased substantially as a consequence of combustion.[24]

Previous works on LBO proximity sensing employed both optical and acoustic based detection.[2] This work focuses on using optical methods, observing the chemiluminescence, due to its direct relationship with the local chemical reaction rates.[25-28] Chemiluminescence is appropriate for understanding the dynamics of the blowout process since it can provide information on the presence and strength of the combustion process in a specific region of the combustor. The primary sources of chemiluminescence in lean hydrocarbon flames are OH (ultraviolet emission around 308 nm), CH (visible emission around 430 nm) and CO_2 (broadband ultraviolet and visible emission).[29-31]

Figure 1 shows the typical, time-averaged flame shapes seen in the combustor close to blowout equivalence ratios. Figure 1a
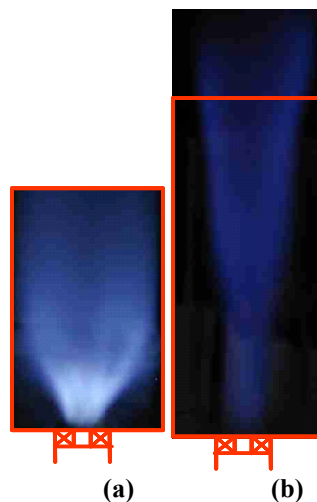

Figure 1. Photographs showing the flame shapes in the combustor: (a) flame for stable equivalence ratios, (b) transient flame very close to blowout shown in a longer combustor.

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shows the flame shape in the combustor, with the border of the picture being the combustor boundaries. The flame mode shape shown in Figure 1b is not stable in this short length combustor and thus was obtained with a longer quartz tube in the combustor. These flame shapes were also observed by Bradley *et al.*[32] in a similar combustor. In the high speed movies, it is observed that the flame tends to jump between these two flame shapes when the combustor is very close to blowout.

Figure 2 shows a typical signal from the fiber probe for two different equivalence ratios and an expanded time trace showing few 'precursor' events. The sudden change in behavior of the signal has been shown to be related to flame loss and recovery in the viewing region of the optical fiber. These precursor events were identified from the signal using thresholding and were found to increase in both number and duration as the LBO limit was approached.[2] This behavior was used for active control of lean blowout using central preinjection pilot. This pilot configuration was found to be better than injecting the same mixture from the center of the final swirler.[4] In a later work,[3] it was shown that the sensitivity of the detection of precursor events depended on the location of the probe collection volume.

Figure 2. Typical time series variation of local OH chemiluminescence signal for ϕ = 0.865 and 0.821. (ϕ LBO = 0.802) The expanded time series for the last case is also shown.

III. Experimental setup

The experiments were performed in an atmospheric pressure, premixed, swirl-stabilized dump combustor. The overall combustor configuration was chosen as a simplified model of a lean, premixed, gas turbine combustor that includes a swirling inlet section. The combustor configuration is the same as used in previous works.[2-4] Premixed gas, consisting of gaseous fuel (methane or natural gas) and air flows through swirl vanes housed in a 23 mm i.d. tube. The swirler consists of two sets of vanes, 30° followed by 45° causing the exit flow to have a (theoretical) swirl number of 0.66.[33] The combustor wall is formed by a 127 mm long quartz tube, which permits uncooled operation of the combustor and facilitates detection of ultraviolet (UV) radiation. The data presented correspond to a bulk average axial velocity of around 4-6 m/s in the combustor under cold conditions. Assuming complete combustion, the average axial velocity of the product gases would be ~20-30 m/s. Since the central pilot tube is ending slightly upstream in this design, the center of the final swirler has a hole in the middle and thus the inner hub of the swirler will appear to be a ring like center body. And the flow through its middle will have lesser swirl than the ones through the final swirl vanes. And also the IRZ will be moved up by a small amount compared to a solid center body, due to the velocity in the center.

Figure 3.   Schematic of the combustor with the movie viewing area and the flame shown.

To help understand the dynamics of the precursor events, a high-speed intensified camera (Videoscope International, Ultracam3) was employed. The camera has a 512×512 CMOS sensor and can record at a rate up to 1000 frames/sec (fps) at this resolution. The image intensifier (GEN III) in the camera has a response from 200 to 700 nm with a gate duration as short as 50 ns. In conjunction with the imaging lens (visible light) employed, the camera is sensitive to all the visible light emitted by the combustion gases. Simultaneously, the chemiluminescence from the combustor was also collected by a fiber optic probe placed 40 mm from the center line and 40 mm above the inlet. The light collected was passed through a 308 nm interference filter (OH chemiluminescence) with 10 nm FWHM and onto a miniature photomultiplier (Hamamatsu H5784-04).
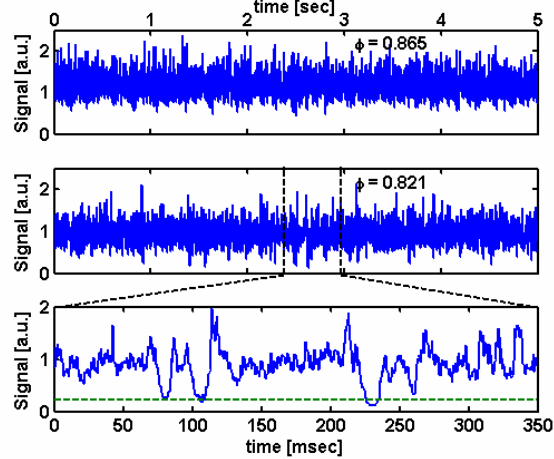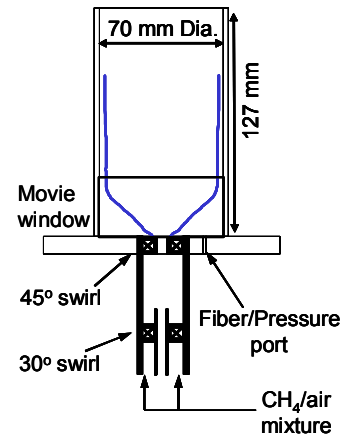
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V. Results

In our prior work[6] it was shown that the extinction event appears to be triggered by a small packet of cold gases entering the IRZ, which lowers the heat release in this zone. The lower heat release in the IRZ causes the zone to become longer and narrower, allowing more unburned gases to appear in the combustor, along the walls. When there is sufficient cold gas around the IRZ, the flame shape appears to split into two parts, one near the inlet of the combustor and the other closer to the combustor exit. The flow field now changes simultaneously as the heat release is not sufficient to suppress the swirl. The new stronger and larger IRZ entrains the hot gases from the downstream combustion zone into the flame zone near the inlet. This feed back from the downstream burning gases to the upstream flame zone, if strong enough, can restore the bottom flame zone and thus restore the whole flow field.
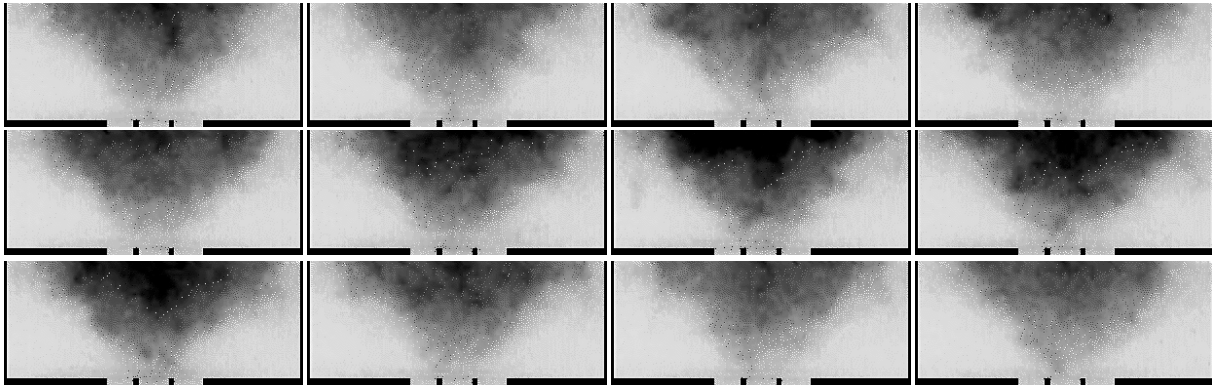

Figure 4. Sequence of (inverted grayscale) chemiluminescence images near inlet of the combustor with equivalence ratio 0.81 (stable operation). The images are separated by 2 msec. Black color in the image corresponds to high intensity and the white, low intensity of chemiluminescence. The time sequence of the images is from left to right on the top followed by left to right on the following rows.

After a few of these precursor events have occurred in a short time, the combustor temperature drops and the overall flame appears to become weaker. If the nominal flow conditions are maintained, eventually the hot gas recirculation is rendered ineffective in restoring the combustion near the inlet. The flame in the combustor blows out soon after this happens.

This work focuses on understanding the dynamics near the inlet of the combustor that leads to the unburned packets that enter the IRZ. Thus the inlet section of the combustor was observed for specific events before a precursor, in order to get an idea of the onset of the precursor events. High speed movies of chemiluminescence emission from the combustor were analyzed with the help of the OH chemiluminescence signal recorded simultaneously from the optical fiber. Only the bottom 30 mm of the combustor is being imaged.

Figure 4 shows a set of frames from chemiluminescence visualization movie of a flame near the inlet with an equivalence ratio of 0.81 at which the combustor is stable. The movie was recorded at 4 kHz and 50 μsec gate time. The dark regions in these inverted grayscale images represent regions of high intensity of chemiluminescence while the white implies low intensity regions in the combustor. The boundary of the combustor is marked by the dark line on the border of the images. The inlet and the annular center body are also indicated. The frames shown are separated by 2 msec in time. The flame in general appears to be stabilized on the center body. However, on instances the flame appears to leave the center body at certain locations. The frames 1-3 show the flame attached to the ring only partly while the frames 5-7 suggest full attachment. Frames 11&12 show that the flame is attached to only the left side of the center body while the frames 3-4 may suggest that the flame is attached only to the right side. The frames 1-2 indicate the projection of the conical flame is attached to either the front or the back on the center body. Similar behavior was observed when the camera was placed at a direction perpendicular to the present viewing direction. This suggests that the flame loses stabilization from the center body partially and the point of loss of stabilization moves in time around the center body. Further analysis showed (data not presented here) that the loss of stabilization on the center body does not follow a constant rate of revolution, however, it moves around in a circular fashion. It was also observed that the loss of stabilization does not occur all the time in the combustor for this stable equivalence ratio. The frame 4 may indicate a brief moment of almost full detachment.

The images in Figure 5 show a set of frames from chemiluminescence visualization movie of a flame with an equivalence ratio of 0.77 at which the combustor blows out within few seconds. The movie was recorded at 4 kHz and 50 μsec gate time. The frames shown are separated by 2 msec in time. The equivalence ratio corresponds to the
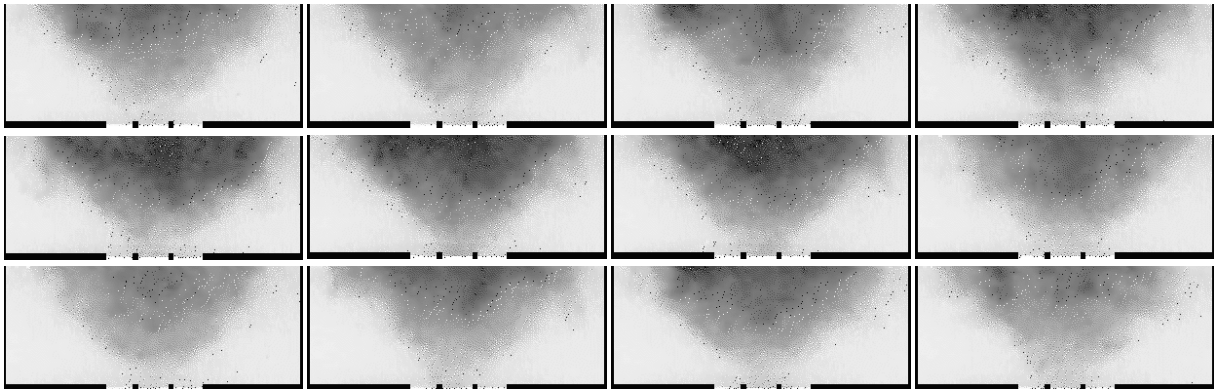
Figure 5. Sequence of (inverted grayscale) chemiluminescence images near inlet of the combustor with equivalence ratio 0.77 (LBO limit). The images are separated by 2 msec. The time sequence of the images is from left to right on the top followed by left to right on the following rows.

blowout limit of the combustor for the flow rate used. The movies of blowout were recorded by running the combustor at a higher equivalence ratio for some time and then quickly decreasing the fuel flow rate to the required value, wait a few seconds and recording the movie. The combustor blew off within 4 seconds of recording. This suggests that temperature of the combustor walls may also be a factor in the blowout process.

The frames shown in Figure 5 indicate that the detachment appears similar to that shown in frames in Figure 4. However, this time there are very few frames over the whole movie where the flame appears to be attached on the whole center body. Frames 6&7 show almost full attachment to the center body while frames 1,9&10 suggest complete detachment and the other frames show partial attachment which moves around. Moreover, in the whole movie, the flame appears to detach almost completely many instances, while the amount of time the flame is fully attached is low.

Observations from movies at several equivalence ratios suggest that this behavior of local loss of stabilization at the center body increases as the LBO limit is approached. Although there is no constant rate of revolution of the attachment point on the center body the flame appears to be returning to the same point over roughly 7-15 msec.
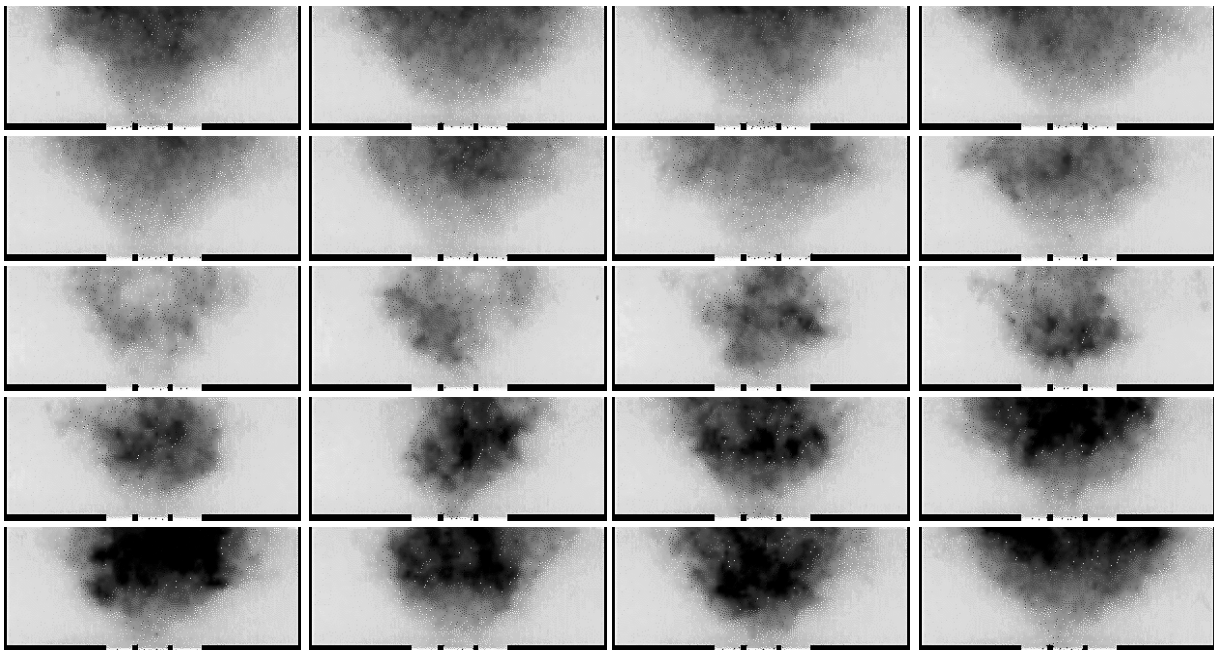
Figure 6. Sequence of (inverted grayscale) chemiluminescence images near inlet of the combustor with equivalence ratio 0.77 (LBO limit) showing a precursor event. The images are separated by 2 msec.

Further analyses indicate that the flame does not favor any particular side over longer periods of time. This suggests that the movement of detachment point is likely the effect of the swirl and the IRZ, which govern the feedback of heat and radicals to the inlet. When a certain point on the center body loses stabilization, the feed back from that point through the inner recirculation gets affected. And due to swirling nature of the flow the weaker feedback is affecting some other point on the center body. This hypothesis is supported by the unbiased movement of the attachment points and their roughly periodic motion.

Figure 6 shows another series of images from the same movie as figure 5 but 115 msec later. This sequence corresponds to a precursor event as described earlier. These images are separated by 1 msec. It should be noted that in this combustor when the PMT data shows a precursor event, the flame is fully lost just above the region being imaged and the flame splits into two parts. One part moving very close to the center body and the other moving almost near the exit of the combustor.[6] From the simultaneous fiber data, frame 4 corresponds to the start of the precursor event and frame 15 roughly the end of the precursor event. The frames 1-3 show that the flame is losing the attachment from the center body. Frame 4 shows that the flame is quite far from the center body, and the precursor event starts. Frames 5-9 shows the extinction part of the event. Frames 10-13 show the packet of flame moving downward to the inlet as observed in earlier studies. And since the flame is closer to the center body, the flame is now able to regain its attachment on the center body. This is shown in frames 13-15. Frame 16 shows the onset of regular combustion as seen in figures 4 and 5.

These observations suggest that the precursor events are an artifact of the flame completely losing its stabilization on the center body. When the flame is lost near the center body the IRZ appears weaker and soon the extinction phase starts. And the recovery of this stabilization occurs through the flame packet that is moved to the center body during a precursor event. The observations that there is more of loss of stabilization as the equivalence ratio is decreased, coupled with the fact that whenever there is a total loss of attachment to the center body, there occurs a precursor event, agrees well with the observed fact that there are more precursor events observed as the
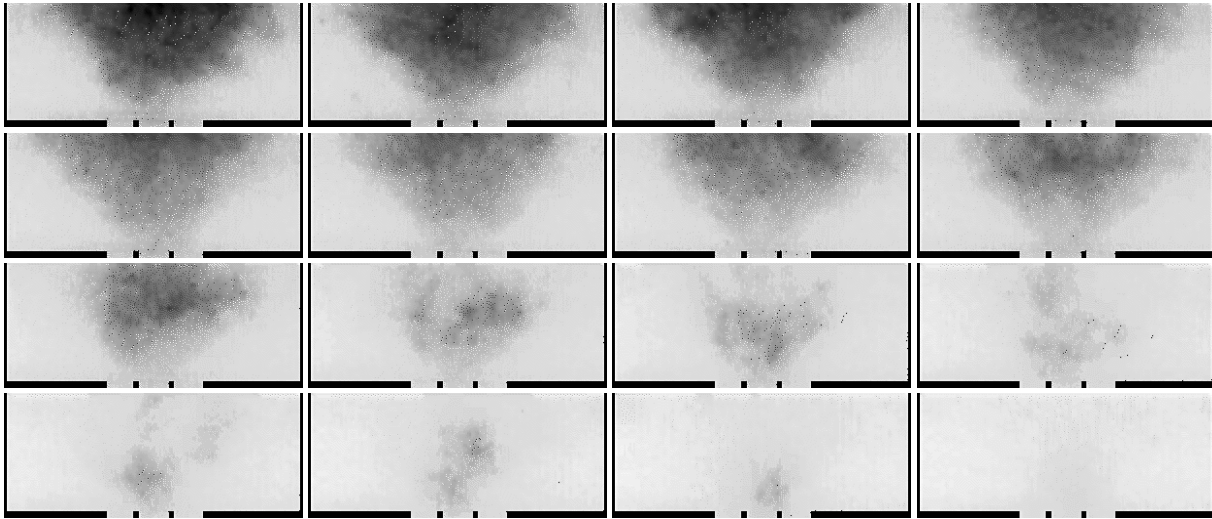

Figure 7. Sequence of (inverted grayscale) chemiluminescence images near inlet of the combustor with equivalence ratio 0.77 (LBO limit) showing blowout. The images are separated by 1 msec. The time sequence of the images is from left to right on the top followed by left to right on the following rows

equivalence ratio is decreased.[3,4] The effectiveness of the central preinjection pilot[4] with slightly richer equivalence ratio while the overall fuel air ratio being constant also supports the current observations, since the injection of slightly rich mixture upstream of the center body will increase the local equivalence ratio of the mixture near the center body and stabilize the flame.

Figure 7 shows a sequence of frames from the same movie as Figure 6&Figure 5, but 3.6 seconds later, when the combustor blew out. It was observed that there were several precursor events between the event shown in figure 6 and this sequence. The frames are separated by 1 msec in time. Frames 1-3 show that the flame is attached partially to the center body. Frames 6-8 show that there is complete detachment from the center body. Frame 8 corresponds to the start of the extinction event from the PMT signal. The flame packet that comes near the center body appears to be weaker than the one shown in Figure 6. This weaker flame apparently fails to stabilize a flame on the center body and sustain the combustion in the whole combustor as observed in earlier work.[6] Even though the flame is able to

hold onto the center body, it is not strong enough to use the recirculation to create a feedback to stabilize itself for longer time and thus the flame extinguishes.

The next main question to understand the dynamics is the mechanism the flame uses to regain the stabilization when there is complete detachment from the center body. As observed in our earlier work, the flame splits into two parts, one near the end of the combustor and the other moves to the center body. Figure 8 shows frames from a movie showing the full length of the longer quartz tube combustor The airflow rate was similar to the other cases but the equivalence ratio was lower than the blowout limit of the short tube combustor. The movie was recorded at 1.9 kHz and 100 μsec gate time. The frames shown here are separated by roughly 1.1 milliseconds. The last image shown is an average image averaged over 105 msec including the frames 1-9. This average image agrees with the photograph of the tornado flame shown in Figure 1. The frames show that there is a stable region of combustion near the end of the combustor. The two vertical lines seen in all the images in Figure 8 at about 1/4th width from either sides are reflections of stray light in the room from the circular quartz walls of the combustor.
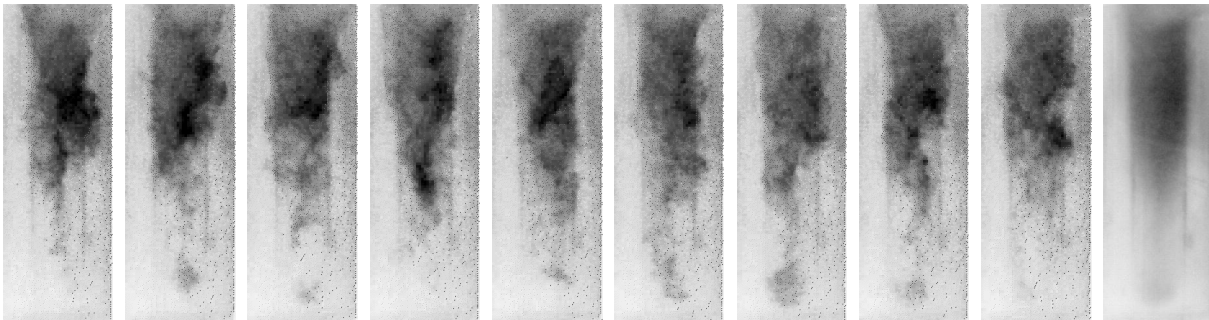

Figure 8. Sequence of (inverted grayscale) chemiluminescence images near inlet of longer combustor with equivalence ratio 0.75 (below LBO limit of short combustor). The images are separated by 1.1 msec. The time sequence of the images is from left to right. The last image is an average of frames over 105 msec.
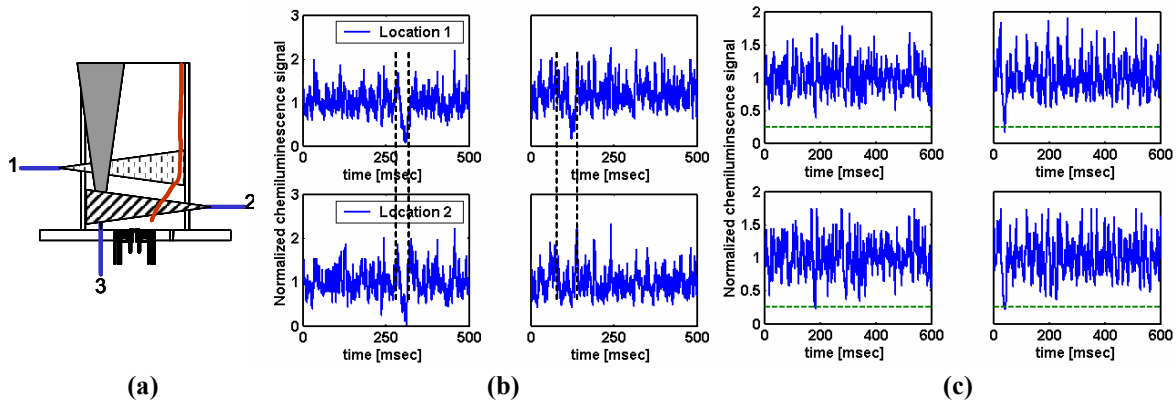

| (a) | (b) | (c) |

Figure 9. Effect of sensor location. (a) Schematic showing the location of the three different probe volumes (b) Two instances of precursor signals as observed from locations 1 (top) and 2 (bottom). The plots on the right show results for a period 3.1 seconds after the left plots. (c) Two instances of precursor signals as observed from locations 1 (top) and 3 (bottom) and threshold. The plots on the right show results for a period 2.1 seconds after the left plots.

Bradley et al[32] have shown that this mode of combustion is mainly stabilized by the hot walls of the combustor. Frames 2-9 show that there appears to be a double helix shaped flame rotating according to the swirl at a certain height from the inlet. The helix can be recognized easily in frames 4-6. Frame 5 shows a projection view of the two helical structures. These helical shapes of the flame were observed in our previous work on understanding the precursor events in the shorter combustor.[6] The double helical structure of the flame was observed clearly only during the precursor events. Frames 5-8 show a small packet of the flame being convected towards the inlet of the combustor. These observations suggest that the recovery mechanism used by the flame when there is a complete detachment from the center body as seen in Figure 7&Figure 8 is through this mode of flame which is stabilized on the hot, side walls of the combustor.

After a few of these precursor events have occurred in a short time, the combustor temperature drops due to heat losses and the overall flame appears to become weaker. As the equivalence ratio is decreased, the transient 'tornado'

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mode also gets weaker and some times the flame that comes to the inlet is unable to establish a stable attachment at the inlet and the flame structure is not restored. Thus flame in the combustor blows out. In case of the short length combustor, the tornado mode is not stable and thus the combustor loses the flame. In case of the longer combustor, the tornado mode stabilizes itself using the hot side walls and thus can sustain a weaker flame mode.

Figure 9 shows results from that work. The locations of the three probe volumes inside the combustor and the signal obtained from two locations simultaneously are shown in Figure 9b-c. Experiments were conducted with two probes at a time collecting data. It was found that the probe location 1 detected more precursor events using threshold method than location 2. Although the flame is detaching from the center body, there is flame in the bottom region due to the flame trying to reattach. This is seen on the second precursor shown for location 2. But if this flame packet is weak or delayed, then we can still detect the event in location 2. Thus the chance of missing the event from location 2 is higher than location 1.

Location 3 on the other hand was found to detect more events than location 1. The partial detachment from the center body and the unburned packets moving around the IRZ can also be sensed by the fiber looking upward from the dump plane and thus will likely sense the most unsteady events. While the fiber looking very close to the inlet sees the flame that comes near the inlet during the precursor event and thus can only sense the loss of flame for very short durations.

VI. Summary and conclusions

Experiments were performed to understand the dynamics of lean blowout in a swirl-dump-stabilized combustor geometry similar to that employed in most gas turbine combustors. The transient events near LBO limit including the extinction-reignition events previously identified as precursors to blowout are investigated in greater detail. The approach was to observe the reaction zone dynamics in the combustor during the transient processes near the blowout limit using simultaneous local OH chemiluminescence data (from a fiber probe) and high speed visualization of chemiluminescence emission from the combustor. The time trace of the OH signal from the fiber probe was used to identify precursor events from the movies. The movies were analyzed to ascertain traits that were common to precursor and blowout events. The movement of the reaction zones was tracked to understand the dynamics. In particular the region near the inlet was observed as prior studies suggested unburned packets entering the inner recirculation zone near blowout.

A theory of dynamics of the blowout process in this combustor is proposed. The precursor event consists of a partial combustor extinction followed by reignition of the main burning region in the combustor. The flame near the inlet is attached to the center body formed by the inner hub of the final swirler. During stable operation of the combustor, the flame is attached all along the perimeter of the center body. Due to turbulent fluctuations, occasionally a part of the flame detaches from the ring and is held by the remaining attachment points. As the equivalence ratio is decreased maintaining the nominal velocity field constant, this partial detachment increases in duration, frequency and the extent of detachment along the perimeter of the center body. This process occurs more often as the equivalence ratio is lowered. This detachment point moves around on the center body in time, not particularly corresponding to a constant angular velocity. This is due to the decreased feedback of heat and radicals from the current detached point to another attachment point through the inner recirculation zone and the swirl. When the flame is detached to a sufficient extent there are unburned packets going around the inner recirculation zone and enters inner recirculation zone from the top. The decreased feedback through the weaker inner recirculation zone now completely detaches the flame from the center body. When this happens, the partial extinction event starts.

The flame instead of being lost completely, appears to split into two parts, one near the inlet of the combustor and the other closer to the combustor exit. Lower heat release near the inner recirculation zone makes the swirl and the recirculation zones stronger and bigger as the heat release is not sufficient to suppress the swirl. This changes the flow field inside the combustor and makes way for the new flame shape, the 'tornado', which is stabilized by the hot side walls of the combustor. In this mode, the flame appears like a double helical structure rotating inside the combustor. Occasionally, this helical flame extends/sends a small reacting packet to the inlet. When this flame that reaches the inlet is sufficiently strong to hold onto the center body, and reestablish a feedback through the recirculation, the original flame shape and flow field are restored. This process is the reignition part of a precursor event.

After a few of these precursor events have occurred in a short time, the combustor temperature drops due to heat losses and the overall flame appears to become weaker. As the equivalence ratio is decreased, the transient 'tornado' mode also gets weaker and some times the flame that comes to the inlet is unable to establish a stable attachment at the inlet and the original flame structure is not restored. In case of the short length combustor, the tornado mode is not stable and thus the combustor loses the flame. In case of the longer combustor, the tornado mode stabilizes itself using the hot side walls and thus can sustain a weaker tornado flame.

This theory of blowout dynamics in this combustor is consistent with the dynamics observed by Muruganandam *et al*[2] that the events get longer and occur more often as the LBO limit is approached. The effectiveness of various collection volume locations in the combustor[3] for sensing is also explained by this theory. The partial detachment from the center body and the dark packets moving into the inner recirculation zone can also be sensed by the fiber looking upward from the dump plane and thus will likely sense the most unsteady events. While the fiber looking very close to the inlet sees the flame that comes near the inlet during the precursor event and thus can only sense the loss of flame for very short durations. The theory also explains the relative effectiveness of the central preinjection pilot[5] in stabilizing the flame when LBO precursors were detected.

With this knowledge of the behavior of the combustor, following suggestions are prescribed for effective avoidance of the combustor blowout. The sensing is most efficient with the fiber port on the dump plane and looking towards downstream. This configuration is also advantageous from material considerations due to lower temperatures in that region. The piloting options for alternate stabilization when the combustor is close to blowout should ensure that the attachment is strengthened. This will ensure that the flame is better stabilized overall and thus can extend the operating range of the combustor to lower equivalence ratios.

VII. References

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