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BLOWOUT CONTROL IN TURBINE ENGINE COMBUSTORS

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ABSTRACT

Detection and suppression of lean blowout (LBO) is demonstrated in liquid fueled, non-premixed combustor, based on previous approaches developed for premixed, gas fueled combustors. OH chemiluminescence from the combustion process was used with a threshold based identification of precursor events. Precursor events are short duration local extinction events occurring closer to the blowout limit. These precursors appear random in time, and occur more frequently as the LBO limit is approached. In the combustor studied here, one region of the combustor was found to be less stable, and thus detection there gave greater sensitivity to LBO proximity. To avoid blowout, redistribution of the total fuel inside the combustor between main and pilot nozzles has been used. The idea is to increase the equivalence ratio near the stabilization region of the combustor and provide a locally more stable combustion zone that can anchor the flame in the rest of the combustor. This moves the effective LBO limit to leaner overall mixtures, thus increasing the LBO safety margin. Two nozzles were used for pilot injection and their effectiveness was compared. The atomization and evaporation of the injected pilot fuel may play an important role in the effective stabilization of the combustor near blowout. The sensing method was found to be working even with the piloting. The location of the sensor was found to dictate the type of control scheme used to prevent blowout, using that sensor.

INTRODUCTION

The reduction of NO_x emissions from ground power and propulsion gas turbines has been a major part of recent programs by government and industry to create cleaner, more environmentally friendly systems. Simultaneously, it is important that design changes maintain (or improve) the efficiency, reliability and performance of gas turbines. Fuel lean combustion has gained interest in the past years due to its potential for very low emissions. For example, premixed natural gas combustors have demonstrated the ability to greatly reduce NOx emissions in ground power generation,[1,2] 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, because the weaker combustion process is more vulnerable to small perturbations in combustor operating conditions. [3,4]

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 engine combustors. 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. Lean blowout in an aircraft engine poses a significant safety hazard for example, during power reductions involved in approach and landing.

For an engine designer, the challenge is to develop a combustor that achieves stable operation and low emissions over the full range of engine conditions. The fuel-air ratio at which LBO occurs (the LBO limit), however, is uncertain; it depends on a number of operating parameters and can change with fuel composition, ambient conditions, and combustor age. This requires the combustor designer to build sufficient 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. Additionally, the allowable operating conditions during power transients of the engine are constrained by the LBO margin. Enhanced combustor performance can, therefore, be achieved by reducing the LBO margin. One approach is an active control system that can sense

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the proximity to LBO and respond appropriately to reduce the risk of LBO.

BACKGROUND

There is a large body of work focused on understanding the mechanisms of flame stabilizations in high velocity streams.[5-10] A number of combustor parameters have been investigated to determine their influence on stabilization characteristics. Bluff body, swirl, dump plane and pilot stabilized flames have been investigated, and flow velocity, swirl number, turbulence intensity, flame holder geometry, mixture composition, temperature and pressure effects have been reported. Since there are numerous differences in conditions between these efforts, the stabilization mechanisms vary between experiments.

A number of specific characteristics of flame behavior associated with LBO have also been studied. Many researchers have observed large scale pulsations of the flame and a few have observed temporary destabilization of the flame in the combustor, before the actual blowout event.[5,11-13] These observations suggest that flames transition from stable combustion to LBO through a transient regime that manifests itself through large scale unsteadiness, local loss of stabilization, and local extinction and reignition events. These transitional events can be used as precursors to LBO. For example, Muruganandam *et al.*[14] demonstrated LBO precursor sensing in premixed, gas-fueled combustors. They detected the optical and acoustic emissions produced by the combustion process. This approach allows nonintrusive detection and improves the robustness of the approach in the harsh environment of the engine.

In subsequent work,[15] they demonstrated control of blowout of the combustor using these precursor events to detect the approach of LBO. They used the direct light emission from the flame (chemiluminescence) to detect the local flame loss events. Control was achieved by splitting the fuel into two streams so as to create a more fuel-rich region that stabilized the combustor without changing the overall fuel-air flowrates. The combustor used in that work was an atmospheric pressure axisymmetric swirl-dump stabilized combustor with premixed methane/air mixture.

The goal of the current research is to extend the previous work to non-premixed, liquid-fueled combustors that are more characteristic of current aeroengine systems. In premixed, gas fueled combustors, the blowout dynamics are mostly controlled by overall fuel-air ratio and local fluid mechanics. In nonpremixed, liquid-fueled aeroengine systems, evaporation of the fuel, and nonuniform mixing of fuel and air lead to significant variations in local fuel-air ratio in the combustor. Thus these systems will likely require modifications to the LBO control approaches developed for premixed systems. Therefore, the focus of this paper is detection of blowout precursors in a liquid-fueled combustor, and the study of a possible actuation method for stabilizing the combustor near blowout.

EXPERIMENTAL

Combustor

The combustor used in this study is a single-cup, annular geometry system based on a commercial aeroengine device. The burner head contains coannular (cylindrical), counter-rotating swirlers. The production model fuel injector, which is located at the center of the swirlers and upstream of the point where the two swirling flows meet, is replaced with a pressure-swirl atomizer for main fuel injection (see Figure 1). The fuel used for these experiments was Jet-A aviation grade petroleum. Air is supplied to the combustor from storage tanks (~1MPa storage pressure) and electrically preheated to approximately 380 K before entering the swirlers. The test-section (~81 cm^2) is optically accessible through quartz side walls. The inner sides of the top and bottom walls, as well as the burner head, are thermal barrier coated. The combustion gases exit through a small converging nozzle to provide a more realistic exit boundary condition.

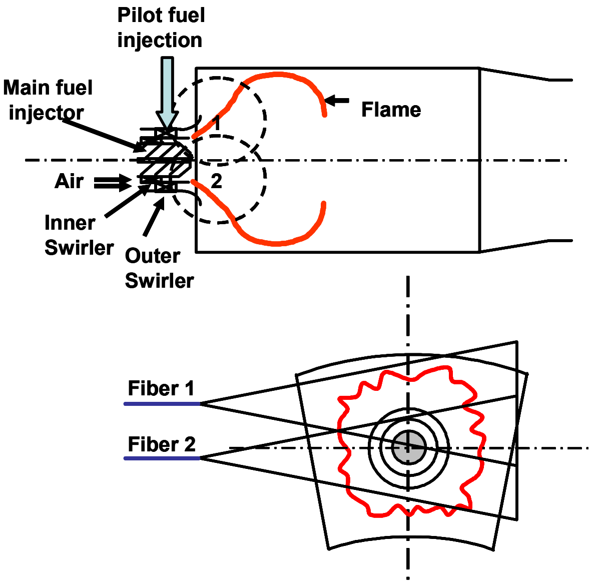


Figure 1. Combustor schematic, including the viewing areas for the optical fibers used.

For the current studies, the combustor was operated at atmospheric pressure with an air flowrate of 40 g/s and fuel rates of 0.96-1.25g/s. This leads to an average axial velocity in the test section of ~20 m/s for the burned gases. When operated with an overall equivalence ratio of 0.4 under these flowrates, the heat release rate is ~45 kW.

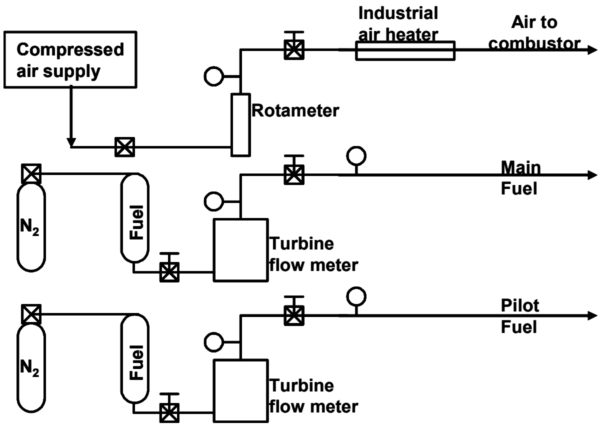


Figure 2. A schematic of the fuel and air flow control and monitoring system.

A schematic of the flow control system is shown in Figure 2. The air was maintained at a constant value for all of the experimental conditions used in this work. Variations in overall equivalence ratio were obtained by varying the fuel flow rate into the combustor. There were separate, manually controlled, flow systems for the main and pilot fuel lines. The resolution of the turbine flow meters used to monitor the fuel flowrates corresponds to a change in equivalence ratio of 0.002. Two pilot fuel injectors were tested. The first was a macrolaminate low flow nozzle (Parker Hannifin) that produces a finely atomized spray. The second was a pressure nozzle produced by constricting the end of a piece of 1/8” stainless steel tubing, which creates a liquid jet when operated in a quiescent environment.

Optical Setup

The chemiluminescence emissions from the combustor were used for LBO precursor sensing. The imaging region for the chemiluminescence collection optics is indicated in Figure 1. The optical setup employs two 365μm diameter fused silica optical fibers. The two fibers are located to collect light from different regions of the combustor near the inlet; fiber 1 looks closer to the top of the combustor and fiber 2 images a region close to the centerline. The fibers have an acceptance cone, half-angle of about 12^o. The collected radiation is passed through an interference filter, centered at 308 nm, (full-width-half-maximum of 10 nm) which corresponds to the OH $A^2\Sigma\text{-}X^2\Pi$ electronic transition. The collected OH emission is detected by a miniature, metal package PMT (Hamamatsu H5784-04). This PMT has a built-in amplifier (bandwidth of 20 kHz) to convert the current to voltage.

To help understand the blowout dynamics, a high speed intensified CCD camera (Kodak Ektapro 239×192 full frame resolution) was used with a UV Nikkor camera lens to visualize the reaction zones in the combustor. Images were recorded at 1 kHz with an intensifier gate time of 100 μsec. The camera, which is sensitive to radiation in the UV and visible, was used without optical filtering. Thus the images obtained include signal from most of the flame emission sources.

LBO SENSING RESULTS

Observables

As noted above, nonintrusive optical and acoustic based approaches have been used for detecting LBO precursors in premixed combustors.[14] Although acoustic methods can also be used to detect LBO precursors in non-premixed combustors[16], this work focuses on the optical radiation from the combustor. While there are a number of sources for optical radiation from a combustor, the source most directly connected to the combustion reactions is chemiluminescence. This radiation is from (electronically) excited molecules that are produced by the oxidation reactions and which can relax to lower energy states by emitting light. Since the intensity of emission is generally proportional, in part, to the chemical production rate of the particular molecule, the chemiluminescence intensity can be related to (specific) chemical reaction rates.[17] For this reason, chemiluminescence has been used previously as a rough measure of reaction rate and heat release rate.[18-21] Thus chemiluminescence can provide information on the presence and strength of the combustion process in a specific region of the combustor, making it well-suited for monitoring flame stability and LBO precursors.

The primary chemiluminescent species of interest in a hydrocarbon flame are electronically excited OH, CH and C_2 radicals and the CO_2 molecule. In lean hydrocarbon flames, OH tends to be the strong emitter, followed by CH with little C_2 emission. As the equivalence ratio increases (more fuel rich), the CH and C_2 emission bands are relatively stronger.[22-24] The present work uses chemiluminescence from OH (308nm) for detecting LBO precursor events, since the OH is strong, and because the UV spectrum has very little interference from blackbody radiation (from walls or particles). Together, these qualities (high signal-to-noise ratio and high signal-to-background ratio) make the OH signal the best choice in terms of observability. Also, optical methods inherently have a fast time response providing fast detection of flame instability events. Finally, optical sensing in general is applicable to a combustor, for example, using fiber optic ports on the combustor walls.

Extinction Events

Experiments were conducted at various equivalence ratios near the LBO limit. Chemiluminescence signals from the combustor showed intermittent events occurring very close to LBO in a similar fashion as observed in the premixed combustor work. Figure 3 shows a comparison of the optical signals over a 0.6 second time frame from the current, liquid-fueled combustor (from fiber 1 viewing the top portion of the combustor) and the previous (premixed) results. The signals have been normalized to facilitate the comparison.

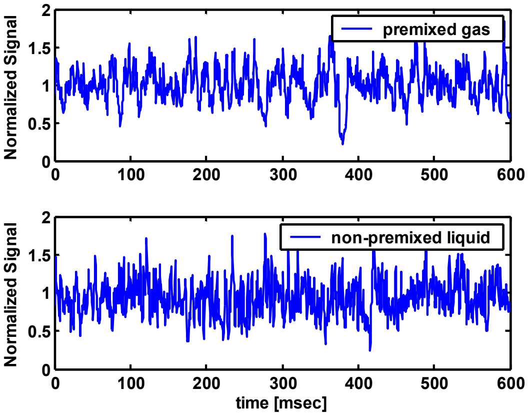


Figure 3. Time series normalized OH chemiluminescence signals showing LBO precursor events from a premixed gaseous fuel combustor[14,15] and the nonpremixed aeroengine combustor.

Both signals exhibit a few, well-defined, partial extinction events. For example, the premixed data shows a significant drop in emission at ~380 msec, while the liquid data does something similar at ~410 msec. The most significant difference between the two combustors is the appearance of many short duration spikes in the liquid-fueled, aeroengine combustor. While there are some similar spikes in the premixed combustor data, there are significantly more of these in the aeroengine combustor. In addition, the amplitude of these high frequency spikes is greater in the aeroengine combustor. One might assume that these spikes are simply an indication of increased noise in the detection system. Though the mean signal from the liquid combustor was smaller than the mean of the premixed system, the increase in the amplitude of the short duration spikes is much larger than the change in the mean signals. Also, these fluctuations are much greater than the electronic noise of the detector. Therefore, it is unlikely the spikes (in either combustor) are due to shot-noise (which scales as the square-root of the mean signal) or detector noise.

Figure 4 shows two sequences of inverted grayscale images from a high speed visualization of the combustor. The conditions were nominally the same for the two cases. The gating time was 100 µsec. The images were rotated such that the top of the combustor appears on the right side of each image. Case (a) shows images that are from a stable combustion period. Case (b) shows a longer sequence which is during a partial flame loss event. In case (a), the sudden change in the intensity (third frame) happens within a 2-4 msec time scale. This sudden change in the intensity is the cause of the spikes noted before. These rapid fluctuations may be due to more intermittent combustion in the non-premixed combustor (compared to the premixed combustor), probably due to atomization non-uniformities or droplets burning individually in a diffusion mode. Thus the optical emission from the liquid-fueled aeroengine combustors has a higher natural intermittency and poses a greater challenge in terms of event identification (as described in the next section).

Case (b) shows a longer sequence showing a partial extinction event. The images are 15 msec apart. This sequence shows that temporarily there is an overall decrease in the intensity of the flame, but the top of the combustor exhibits greater flame loss than the bottom of the combustor. Thus the resultant flame appears to be present only in the bottom half of the combustor (left side of the images). This behavior suggests that the combustor has a weaker stabilization near the top of the inlet section.

Event Identification

The double threshold based method for identifying precursors, used in the previous work is adopted here. This method defines a start of a precursor event when the signal level drops below the lower threshold, and defines the end of the event when the signal level goes back above the upper threshold. The difference between lower and upper threshold is used to decrease the noise in the signal which can cause false/extra events. As the number of precursor events is expected to increase near blowout, it would be undesirable for the identification method to give extra events, as it might lead to erroneous conclusions about proximity to blowout. In the earlier work, the threshold values were defined to be a preset fraction of the local mean. For example, the signal dropping below 50% of the recent mean could start an event, which then ended when the signal went above 70% of the same mean. With the signal normalized by the recent mean, the event identification is robust with regard to long term variations in power setting, transmission efficiency of the optics and detector response.

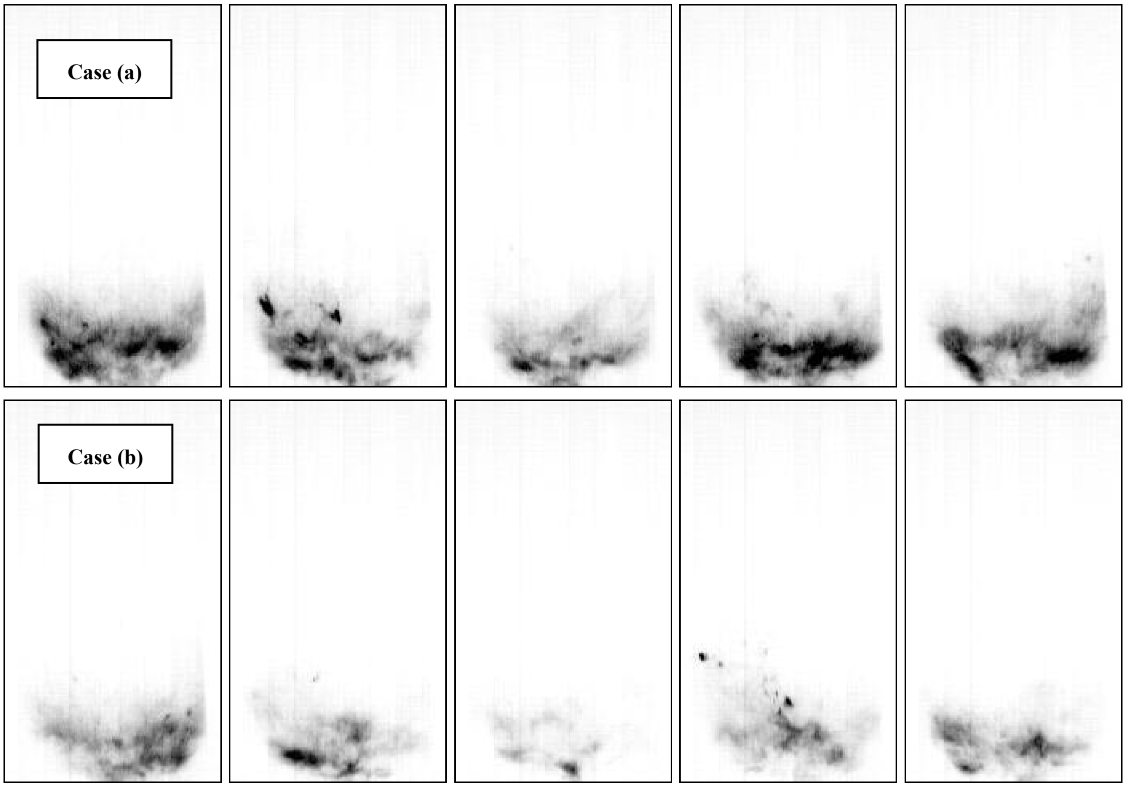


Figure 4. High speed visualization images (inverted grayscale) of a nominal flow condition: case (a) is sequence of images showing intermittency of combustion; time between images 2msec; case (b) shows a precursor event; time between images 15 msec. The images have been rotated such that the flow is upward, and the top of the combustor corresponds to the right side of the images.

The challenge in the liquid combustor is to find a method for setting the thresholds that takes into account the much larger degree of natural combustor intermittency. The approach chosen here is based on the recent statistics of the signal, in parallel to the mean normalization. Specifically, the threshold spacing is based on the recent standard deviation (σ) of the signal, which is primarily determined by the natural intermittency. So, the lower threshold, which begins an event, was again defined to be 50% of the local mean, but the upper threshold was defined to be 2σ above the lower threshold (see Figure 5).

The choice of two standard deviations provides significant suppression of the intermittent spikes. For example, if the threshold difference was chosen to be one standard deviation, then there is a 30% chance the spikes would prematurely end the event (if the amplitude of the spikes is normally distributed). With a 2σ difference, there is only a 5% probability that any spike would prematurely end an event. This is illustrated in Figure 5, which shows a precursor event with a spike that crosses the 1σ line. Since the signal than falls below the 50% lower threshold almost immediately, the event identification scheme would find two events instead of one. The 2σ upper threshold does not have this problem. However, it should be noted that in this case, the 2σ threshold requires the signal to *rise above the mean*. While not a problem in the case shown in Figure 5, this could result in an artificially long duration event. Thus the optimum threshold separation may lie between 1σ and 2σ if σ is significant compared to the mean value (for example, more than one-fourth of the mean).

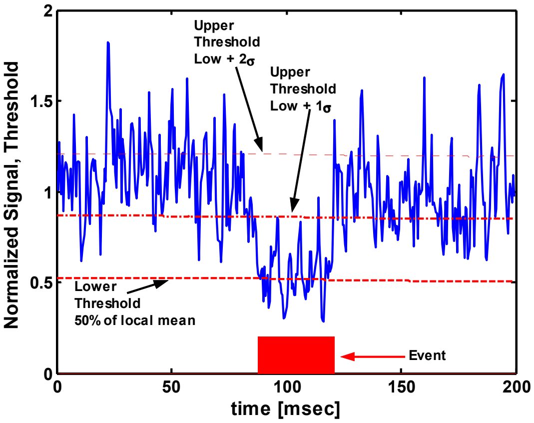


Figure 5. Illustration of the double threshold scheme showing the lower and upper thresholds with the signal, and the identified event.

Figure 6 shows how the events change with overall equivalence ratio as LBO is approached ($\phi_{LBO} \approx 0.385$ for the current conditions). Results are shown for both sensor locations. The average number of events per second (based on a 16 second data trace) tends to increase as the LBO limit is approached. Similarly, the average duration of an event also increases as the combustor becomes less stable. These trends are similar to that observed in the premixed combustor. This indicates that in both the premixed and non-premixed combustors, the proximity to LBO can be characterized by increased occurrence of temporary, local extinction events associated with fluctuations in combustor conditions. The increased duration of the events as one approaches LBO suggests that the extinguished fuel-air pockets may either become larger or harder to reignite or the rest of the combusting region is weaker and less able to reignite the gases.

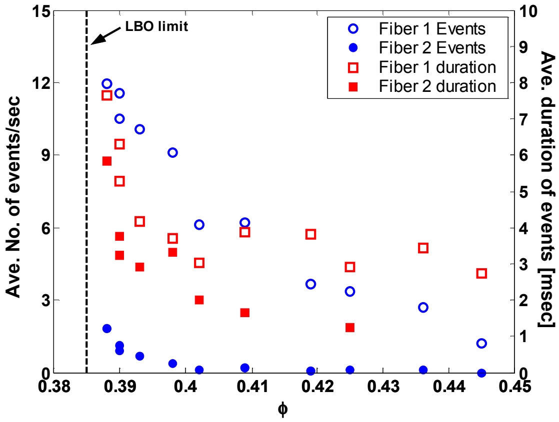
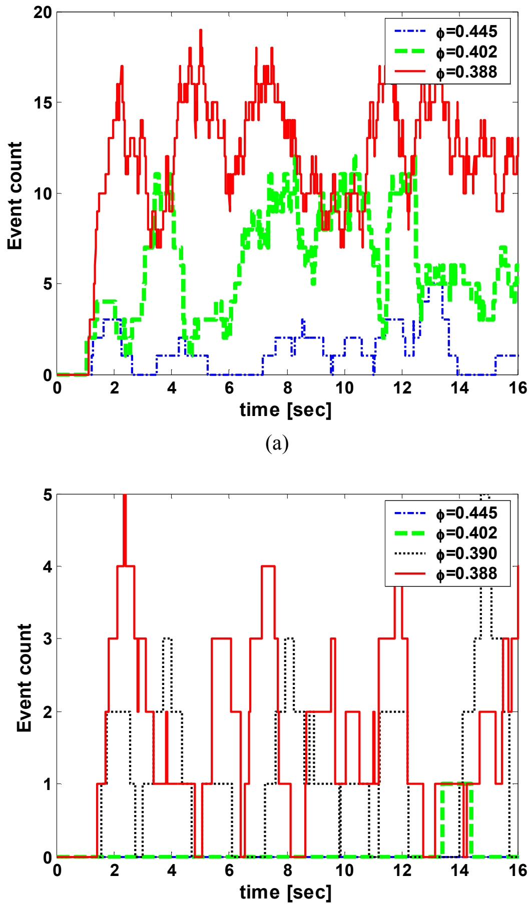


Figure 6. Variation of average number of events per second and the average duration of each event as a function of equivalence ratio. The dotted line indicates the LBO limit for the combustor.

One significant difference between the current results and the earlier premixed data is the duration of the events, which are typically 2-5 times longer in the premixed combustor. There is also a large difference between the data from the two sensor locations in the liquid combustor. Fiber 1, which views the upper portion of the combustor, captures significantly more and longer events than the centerline sensor (see Figure 6). This indicates the flame is less stable (or "weaker") in upper location. This is also supported by the partial extinction of the flame on the top half of the images during the precursor event (see Figure 4).

The first point where the loss of stability occurs will most likely be the point where the stability is weakest, viz., the top of the combustor. It was observed that when the signal from fiber 2 indicates an extinction/precursor event, fiber 1 also detects the event most of the time. This suggests that events seen by fiber 2 may be more global compared to those seen by fiber 1. However, data from fiber 1 will likely be more sensitive to the approach of blowout compared to fiber 2 data in this combustor. Since partial flame loss events usually precede global flame loss precursors, it may be better to use data from fiber 1 for the purposes of early detection of proximity to blowout.

Thus, it is shown that the likelihood or duration of events increase with proximity to LBO. These parameters can therefore be useful in a control system to raise an alarm on the approach of blowout. For example, Figure 7 shows the time trace of number of events detected in a one second moving window for several equivalence ratios. This demonstrates the random occurrences of these events with the average number of events increasing as LBO limit is approached. A control system could programmed to respond when the number of events becomes significant. For example, if the event count from fiber 1 exceeds ten (or equivalently one count from fiber 2), the control system could engage an actuator to enhance the stabilization of the combustion process. This is the topic of the next section of the paper.



(a)

(b)

Figure 7 Event count in the previous 1 second, as a function of time for a few equivalence ratios (a) for the fiber 1 (b) for the bottom fiber 2.

COMBUSTOR STABILIZATION RESULTS

Methods

The primary goal in for an LBO control actuator is to provide either an alternate stabilization mechanism for the flame or to increase the strength of the current stabilization point. In the earlier work,[15] redistribution of the fuel inside the combustor was employed. The redistribution of the fuel was accomplished by injecting a certain fraction of the total fuel flow through a pilot injector located near the apparent stabilization zone in the premixed combustor. It was concluded that this produced a locally more fuel-rich region that was able to stabilize the flame zone in the rest of the combustor. Here, we investigate a similar approach for stabilizing the liquid, aeroengine combustor near blowout.

Piloting Options

From the high speed visualizations, it appears that the flame is anchored in the shear layer that lies between the two counter-rotating swirl flows. To enhance the "strength" of this stabilization region, the goal is to inject a larger fraction of the fuel (the "pilot" fuel) there. Since the swirlers cannot be easily modified to accommodate a pilot fuel injection in the separator lip, it was decided to inject the pilot fuel through one of the swirlers, upstream of the main fuel injector located in the center of the inner swirler. Again because of the inability to modify the production model swirlers, and restricted access to the burner head through the inlet section walls, we were limited to injecting the pilot fuel into the outer swirlers and to only one of the azimuthal flow passages. This azimuthal location resulted in the injected fuel leaving the swirler at the top of the combustor. However, the swirler exit is located upstream of the point where the two swirling flows meet, thus the azimuthal location where the pilot fuel is actually injected into the combustor test section will likely be closer to the side of the combustor.

Two pilot fuel injectors were used: 1) a finely atomized, commercial macrolaminate injector and 2) a simple, pressure nozzle injector. The macrolaminate spray nozzle was located next to the inlet of the swirl vanes. The pressure nozzle was located at the entrance of the swirling passage.

Figure 8 shows the effect of both the pilot configurations on the blowout limit of the combustor. The atomizer appears to have some decrease in blowout equivalence ratio at the lower pilot fractions, but loses its effect as the pilot fraction increases. The pressure nozzle on the other hand, has a weaker effect at low pilot fractions, but continues to reduce the blowout equivalence ratio for higher pilot fractions. For both pilot injectors, visual observation of the flame suggests that there is near complete combustion of all the fuel entering the combustor. There is no significant change in the location of the visible flame radiation, and the flame does not extend beyond the combustor test section exit. Thus we conclude that piloting does in fact stabilize the overall combustion zone for equivalence ratios below the unpiloted blowout limit.

The differences behavior of the two injectors can be attributed to differences in their atomization characteristics. The macrolaminate injector produces good atomization of the fuel only for the higher pilot fractions (higher flow rates), which are closer to its designed operating range. At the high pilot fractions, the well atomized fuel spray may evaporate too quickly after coming in contact with the heated air or the hot metal of the swirlers. The pressure nozzle, on the other hand, produces a thin, poorly atomized, jet at all the flowrates (based on observations in quiescent conditions). Thus it should produce a less well mixed, less evaporated fuel flow.

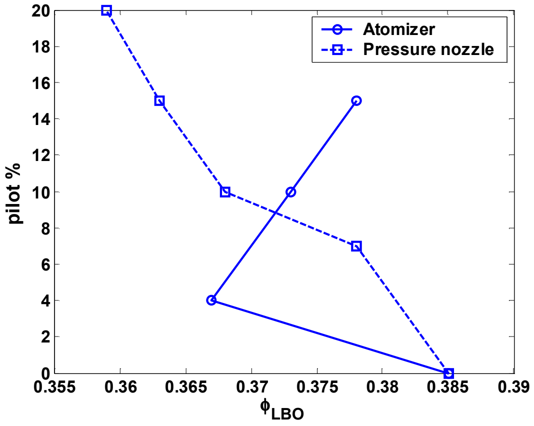


Figure 8. Variation of the blowout equivalence ratio with various pilot fractions for the two injector configurations investigated.

Redistribution of the fuel to the pilot requires that the main fuel flow be decreased (since the overall equivalence ratio is fixed). Thus the main combustion process is being deprived of fuel when the pilot fraction is increased. The pilot fuel is injected in order to increase the stabilization of the combustion process a some region of the combustor. If that region is stabilized *and* can in turn stabilize the rest of the combustor (which is less stable on its own due to the reduced main fuel flow), then the result is improved combustor stability and a decrease in the blowout equivalence ratio. Based on this reasoning, it appears that the fine atomization of the pilot fuel does not give an overall improved stabilization, while the poorly atomized pressure nozzle pilot does provide a useful tradeoff between pilot region stability and weaker combustion in the rest of the combustor.

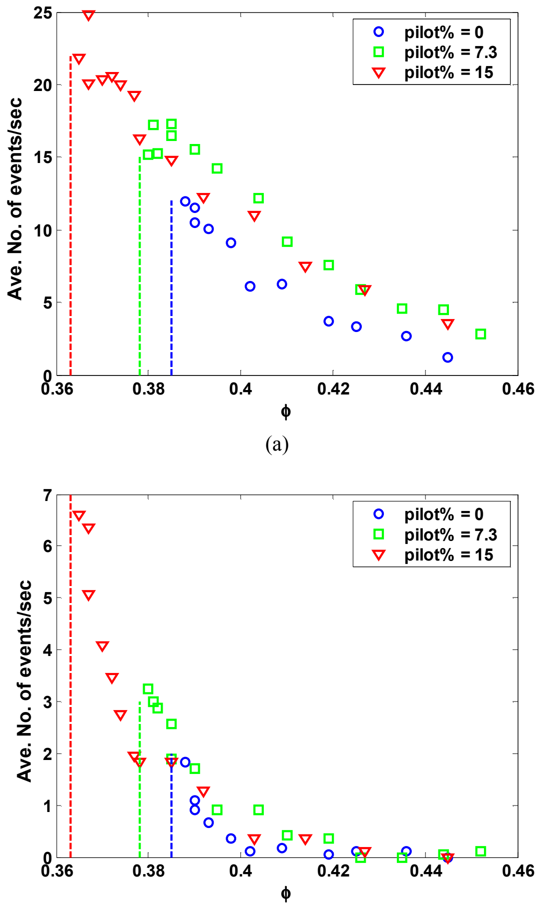
In the current, non-premixed combustor, a decrease in (overall) blowout equivalence ratio of 6% was attained for a pilot fraction of ~15% (with the pressure nozzle). This can be compared to the earlier results for the premixed combustor, where the blowout equivalence ratio was reduced by 6% for only a 12% pilot fraction. Thus the effectiveness of the pilot is not as good in the current setup. This may be due to the fact that the pilot fuel is injected non-axisymmetrically in the current work. The azimuthal location of pilot injector was decided based on the ease of access and not based on the best possible injection point. This may also be critical in deciding the payoff from the piloting.

Effect of Pilot on LBO Sensing

Since the pilot injection can change the dynamics of the combustor near the LBO limit or change the spatial extent of the active combustion region, it might influence the efficacy of the LBO precursor sensing. Thus the effect of piloting on the sensing technique was investigated through open loop tests. Figure 9 shows the effect of pilot fraction on the LBO behavior, for the pressure nozzle only. As observed above the LBO limit (vertical lines) moves to leaner mixtures with increasing piloting. The average number of events detected per second as a function of equivalence ratio is also indicated for each pilot fraction case. The sensing approach described above successfully identifies precursor events with piloting. As in the unpiloted case, the number of events increases with a reduction of the overall equivalence ratio, i.e., as LBO proximity increases.

The results from premixed combustor[15] show that higher pilot fraction increased the likelihood of events slightly at ϕ farther from the blowout limit and decreased it when the overall ϕ was closer to the blowout limit. Essentially, with increasing pilot fraction, the curve of events versus ϕ shifted to the left, with a small shift upwards at ϕ farther from LBO limit. Thus in the premixed combustor, the number of extinction events seen by a detector was a good indicator of increased combustor stability near blowout. In the non-premixed combustor, the results from fiber location 2, has a similar behavior as that from the premixed combustor. However, the results from fiber location 1 indicates that piloting decreases the blowout limit, while it appears to increase the occurrence of precursor events, for a given overall ϕ, compared to the no pilot case. In addition, the higher pilot fuel fraction (15%) produces less events than the low pilot case (7.3%).

To understand this discrepancy, one must remember that pilot fuel is not being injected axisymmetrically. Since fuel is only injected at one location around the circumference, it is likely that the improved stabilization is highly localized azimuthally in the combustor. If the detectors are not viewing this region (or not solely viewing this region), they are likely viewing areas with reduced ϕ, which are less likely to be stable. Since in the piloting method used, the injected pilot fuel tends to enter the combustor from the side rather than the top azimuthal location, fiber 2 has a higher chance of viewing the stabilized zone than fiber 1. Therefore, the observation of increased number of events with piloting could change if the pilot fuel were distributed more uniformly or if the sensing locations were changed.



(b)

Figure 9. Variation of average number of events/sec with equivalence ratio for piloted and non piloted cases. (a) data from fiber 1, (b) data from fiber 2.

The previous work, in premixed combustor, used the control algorithm based on the number of precursor events per second. When the number of events increased as the LBO limit was approached, the pilot fraction was increased to make the combustor more stable. This decreased the number of precursors. Thus the control scheme had an objective to decrease the number of precursors by increasing the pilot fraction. In the non-premixed combustor, the same control approach can be used with the sensor location 2 since this signal behaves similar to that of the premixed combustor. On the other hand, with sensor location 1, the increased piloting does not decrease the number of events, but still makes the combustor stable. Yet since the pilot effectively moved the blowout limit away from the operating condition, this pilot can be used in a two state (ON/OFF) mode, to help the controller handle transient conditions where LBO limit is approached for a short duration.

SUMMARY AND CONCLUSIONS

We have demonstrated the detection and prevention of lean blowout in a non-premixed, liquid-fueled combustor. The sensing and control methods developed in a prior study[15] for premixed, gas-fueled combustors have been extended and modified for use in an aeroengine-type combustor.

Extinction events are detected in the flame chemiluminescence emissions. Here, the OH chemiluminescence was collected by optical fiber probes. The main difference in the optical signal between the previous premixed gas fueled combustor and the nonpremixed liquid fueled combustor is a greater amount of intermittency in the latter. This is likely a result of spatial and temporal fluctuations in the local fuel concentration due to nonuniformities in the atomization, evaporation and mixing processes. The natural intermittency of the combustor acts like a source of noise that makes the detection of precursor events more difficult.

An LBO precursor event is identified with a double threshold method. An event is defined to begin when the signal drops below a lower threshold level equal to some fraction (50% here) of the local mean signal. The event is identified as ending when the signal rises above an upper threshold level. To account for the natural intermittency of the liquid combustor, the upper threshold is based on the recent standard deviation (σ) of the signal. For example, the upper threshold can be defined to be equal to the lower threshold value plus twice σ. Both the number of precursor events and their average duration increase as the overall equivalence ratio of the combustor approaches the LBO limit. This behavior is similar to that in the gas fueled, premixed combustors.

High speed visualization indicated that there is poorer flame stabilization near the top of the combustor inlet. Detection of precursor events in this region was found to be more sensitive. Thus placement of the LBO sensor should take into account any known variations in the flame stability.

Control of lean blowout was achieved by enhancing stabilization with fuel redistribution inside the combustor. A fraction of the total fuel was redirected to a pilot fuel injector. Two types of pilot injector nozzles were used: an atomizing nozzle and a pressure jet nozzle. While both nozzles were able to reduce the LBO limit, the pressure nozzle was found to be more effective in stabilizing the combustor. This pilot decreased the blowout equivalence ratio by 6% at 15% pilot fraction. This is somewhat comparable to the 6% at 12% pilot fraction observed in the gas fueled premixed combustor.

Since redistribution of the fuel to the pilot requires that the rest of the flow be deprived of fuel (for constant power control), it is important the improved stabilization in the pilot region outweigh the weaker combustion elsewhere. This balance appears to depend on the atomization characteristics of the pilot injectors. Fine atomization of the pilot was unsuccessful compared to the poorly atomized pressure nozzle. However, this may be partly a result of the injection of the pilot fuel at only one azimuthal location in the current setup.

The LBO precursor sensing successfully tracked the increase in LBO margin with greater pilot fraction. As LBO was approached, the number of events increased. Though piloting increased overall combustor stability, it also produced more flame loss events for a given overall ϕ farther from blowout. When close to blowout limit, the piloting tends to decrease the precursor events for sensor location 2, in a similar fashion like the earlier premixed combustor results. Thus sensor 2 can be used with a control scheme, which when the event count exceeds a critical value, increases the pilot fraction to stabilize the combustor and decrease the event count. The primary goal of this controller is to suppress precursors using piloting.

Sensor 1 on the other hand, detected more events for higher piloting for all equivalence ratios. In other words, increasing the pilot fraction for a given power setting can actually increase the number of precursor events, which a control system might misinterpret as an indication of closer proximity to LBO. This counterintuitive result may also be related to the non-axisymmetric injection of pilot fuel. It is likely that the improved stabilization in the current setup is highly localized azimuthally, and the sensors were likely viewing regions with reduced ϕ, which are thus less stable. Thus the relationship between event count and LBO proximity may change for a combustor with better access for fuel injection, location of the sensor, or if other, less localized, stabilization methods are employed.

Even in the current configuration, a control system could use the sensor 1 to give earlier detection of approach of LBO, and use the pilot in a two state mode. If the LBO sensors detect more than some allowable level of events in a given time window, the control system would turn piloting on to a preset value, and only turn it off after the overall combustor conditions have sufficiently changed, i.e., until the overall fuel-air ratio demanded by the operator has been increased. This controller would be useful to protect against blowout during transient conditions, where the LBO limit is approached only for a short duration.

The detection and suppression of blowout phenomenon has been demonstrated in both premixed and poorly atomized non-premixed combustors. The same approach was employed in these two combustors that are almost two extremes in combustor design. Hence, it can be expected that a well optimized non-premixed combustor design can utilize similar control schemes to detect and suppress blowout. In addition, futuristic, lean, low NOx emissions combustor designs can use these approaches to stabilize the combustor when blowout is approached.

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