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School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA

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AN ACTIVE CONTROL SYSTEM FOR LBO MARGIN REDUCTION IN TURBINE ENGINES

M. Thiruchengode[1], S. Nair[1], S. Prakash[1], D. Scarborough[2], Y. Neumeier[3],
J. Jagoda[4], T. Lieuwen[5], J. Seitzman[6], B. Zinn[7]

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0150

ABSTRACT

A complete, active control system has been developed to permit turbine engine-like combustors to operate safely closer to the lean blowout (LBO) limit, even in the presence of disturbances. The system uses OH chemiluminescence from the combustion process and a threshold based, event definition to detect LBO precursor events. These precursors appear random in time, and occur more frequently as the LBO limit is approached. When LBO precursors are detected, fuel entering the combustor is redistributed between a main flow and a small pilot, so as to increase the equivalence ratio near the stabilization region of the combustor. This moves the effective LBO limit to leaner mixtures, thus increasing the safety margin. The control system was demonstrated in an atmospheric pressure, methane-air, swirl-stabilized, dump combustor. The NO_x emissions from the piloted combustor were found to be lower than from the unpiloted combustor operating at the same safety margin and nominal velocity field. The controller minimizes the NO_x by reducing the pilot fuel fraction at constant total power setting until an unacceptable number of precursor events are observed. A set of control options for custom operation of the controller for a specific combustor are discussed.

INTRODUCTION

The need to develop cleaner, more environmentally friendly power and propulsion systems has driven interest in reducing pollutant emissions, while simultaneously maintaining (or improving) efficiency, reliability and performance. This drive towards reduced pollutant emissions has prompted interest in combustion under increasingly fuel lean conditions. 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, because the weaker combustion process is more vulnerable to small perturbations in combustor operating conditions.

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. 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). Enhanced performance will require a reduction of this LBO margin. For the purposes of this work, safety margin from LBO is defined as the difference in equivalence ratio between the operating condition and the LBO limit for the same nominal velocity field and inlet temperature.

A number of specific characteristics of flame behavior associated with LBO have been studied by researchers. For example, Nicholson and Field[1] observed large scale pulsations in the flame as it was blowing off. They also reported that the main flame detached and reattached to the flame holder before extinguishing completely. Chao *et al.*[2] observed similar phenomenon in a non-premixed turbulent jet flame during the blowout process. They reported that prior to

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[1] Graduate Research Assistant, AIAA Student Member
[2] Research Engineer I, AIAA Member
[3] Adjunct Prof., Senior Research Engr., AIAA Member
[4] Professor, AIAA Associate Fellow
[5] Assistant Professor, AIAA Member
[6] Associate professor, AIAA Associate Fellow
[7] Regents Professor, AIAA Fellow

blowout, the flame alternated between attachment and detachment to the burner lip. They also noted that this process can last a few short cycles or up to several seconds. Hedman *et al.*[3] imaged the OH radical distribution in a premixed natural gas/air combustor using PLIF. They observed significant flame instability near lean blowout and noted that there was a significant amount of time when there was essentially no OH present in the combustor. Thus it has been observed that flames transition from stable combustion to LBO through a transient regime that manifests itself through large scale unsteadiness, and local extinction and reignition events. These transitional events can be used as precursors to LBO; for example, Muruganandam *et al.*[4] demonstrated LBO precursor sensing with optical and acoustic methods.

These LBO precursors can be used by an active control system in order to allow combustors to run at leaner equivalence ratios, compared to the present combustors. This would permit reduced NOx emissions without loss of safety. Since the primary operator input is power level, i.e., fuel flow rate, it is important that the control system reduce the LBO margin without changing the fuel flow rate. This can be achieved by redistributing the fuel in such a way to increase the equivalence ratio near the stabilization zone in the combustor (piloting). In this effort, an active control system is developed to detect the approach of LBO and to split the fuel between main and pilot flows to stabilize the flame in the combustor and thus increase the safety margin for low NOx combustors. The remainder of this paper includes a description of the experimental hardware used to demonstrate active control, details on the LBO precursor sensing and the fuel control actuation approaches, the design of the controller, and performance results for the components and the complete control system.

EXPERIMENTAL

Combustor

The experiments were performed in an atmospheric pressure, premixed, swirl-stabilized dump combustor. A schematic of the combustor is shown in Figure 1. The overall combustor configuration was chosen as a simplified model of a lean, premixed, gas turbine combustor that includes a swirling inlet section. This is a good model for ground power turbines, and lean prevaporized, premixed (LPP) combustors being developed for aircraft propulsion. 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.[5] The swirlers are spaced by about 50 mm. 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. A rectangular section glass tube was also available for schlieren imaging studies of mixing in the combustor. The data presented here correspond to a bulk average axial velocity of around 4 m/s in the combustor under cold conditions. Assuming complete combustion, the average axial velocity of the product gases would be ~20 m/s. The flow control and monitoring system has a resolution that is equivalent to a change in equivalence ratio (ϕ) of approximately 0.003. A thermocouple was used to monitor the change in the temperature of the combustor wall, as this by itself can cause LBO limit to change. For most cases during our experiments, the external wall temperature was in the range 400-500 K. The exhaust gas analysis was carried out using Land Instruments International Ltd., LANCOM series II portable flue gas analyzer. This system had an accuracy of ±1ppm for NO and CO measurement.

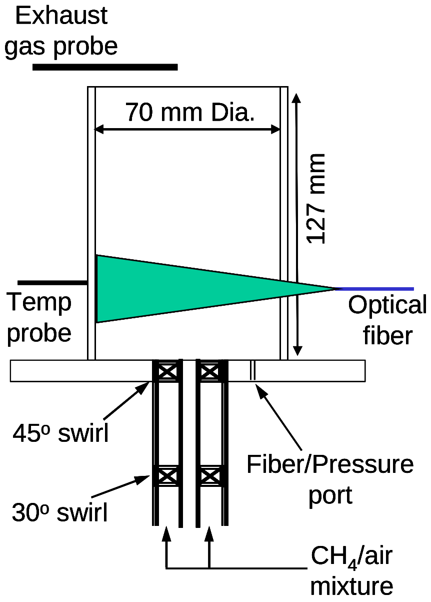

Figure 1. Combustor schematic showing the viewing areas for the optical fiber used.

Optical setup

The imaging region for the chemiluminescence collection optics setup is also indicated in Figure 1. The optical collection setup employs a 365µm diameter fused silica optical fiber. The fiber has an acceptance cone half angle of about 12°. The collected radiation is passed through an interference filter, centered at 308 nm, (full-width-half-maximum, FWHM of 10 nm) which corresponds to the OH $A^2\Sigma$-$X^2\Pi$ 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 and operates from a 12VDC source.

To help understand the combustor behavior, 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 of 200 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.

Control system

The schematic of the flow system is shown in Figure 2. Both fuel and air lines are double choked before the spilt between main and pilot lines, and thus the total flow rates can be maintained at constant values throughout the experiment. The split between the pilot air and the primary air was fixed at a constant value throughout this study.

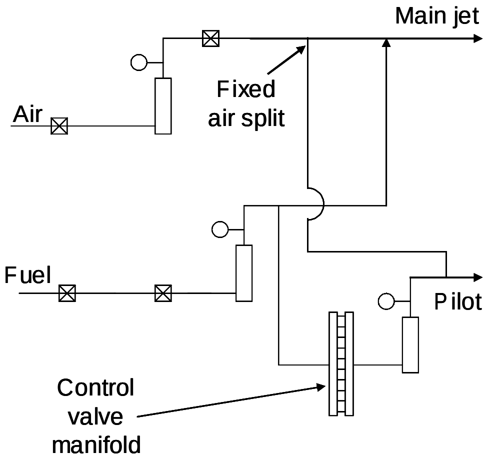

Figure 2. A Schematic of the flow system showing the fuel split and the control valve manifold.

For steady operation, the split of the fuel between the primary and the pilot flows could be adjusted with manual valves. However, the active control system required controllable valves with good time response, repeatability, and flexibility. Therefore, the fuel split was varied with a set of ten miniature solenoid valves (AM1124, Asco Scientific). These 2-way valves operate at 24 V, normally closed, for pressures up to 110 psi (76 kPa), and have an orifice size of 0.64 mm. The control signal was a 5V signal from the control computer, which activated a set of relays to switch these valves at 24V. The valves were connected in parallel in a central manifold. Therefore, increase fuel flow through the pilot was attained by increasing the number of open valves, or the amount of time that the valves were open.

The control program used in this study was developed for the QNX real-time operating system running on a Pentium IV 1.5 GHz computer. It was used to process the optical signals and output the command signal to the valves. The real-time input and output are supplied at a sampling rate of 20 kHz by different IO boards (PowerDAQ PD2-MF-64 and PD2-AO-32, United Electronic Industries, Inc.).

LBO SENSING TECHNIQUE

Observables

To improve robustness in the harsh environment of the engine, a nonintrusive sensor that can be located outside the high pressure, high temperature combustor is desirable. This nonintrusive requirement combined with system simplicity leads to two main sensing options: detection of electromagnetic or acoustic radiation produced from within the combustor. While there are a number of sources for electromagnetic 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 chemical reactions and which can relax to lower energy states by emitting light. Since the intensity of emission is generally proportional to the chemical production rate of the particular molecule, the chemiluminescence intensity can be related to chemical reaction rates.[6] For this reason, chemiluminescence has been used previously as a rough measure of heat release rate and even equivalence ratio.[7-9]

The primary chemiluminescent species of interest in a hydrocarbon flame are electronically excited OH, CH and C_2 radicals. In lean hydrocarbon flames, OH tends to be the strong emitter, followed by CH with little C_2 emission. As the equivalence ratio increases (richer), the CH and C_2 emission bands are relatively stronger.[10,11] This work uses chemiluminescence from OH (near 308 nm) for detecting lean blowout since this emission is the strongest. The UV spectrum produced by OH also has very little interference from blackbody radiation (from walls or particles) and thus has good observability.

Since chemiluminescence is directly related to (some) chemical reaction rates, it can provide information on the presence and strength of the combustion process in a specific region of the combustor. This approach is appropriate for monitoring the flame stability and LBO. Also, it inherently has 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. Acoustic radiation is also emitted by the combustion process, specifically from unsteady heat release, which causes volume expansions in the combustor. Both chemiluminescence (optical) and acoustic pressure measurements have been used for detection of LBO precursors by Muruganandam *et. al.*[4] In this work, the optical approach is used for simplicity of control.

LBO Precursor 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. Figure 3 shows examples of optical sensor outputs at a stable equivalence ratio and one near LBO.

Overall, the mean OH chemiluminescence signal decreases as the fuel is reduced. More importantly as the LBO limit is approached, a number of sudden reductions in the OH emission are observed, with signal levels going well below the mean value. This is more clearly seen in the expanded optical emission time series data. Often, these events are characterized by an almost complete loss of chemiluminescence quickly followed by strong emission from the imaged region.

A closer investigation of these events using high speed visualization (Figure 4) shows that the flame in the combustor vanishes for a short duration and then reappears. The flame, when it reappears, is temporarily more intense. This intense combustion appears to initiate a regular (more stable) combustion process, until the next event occurs. These unique extinction and reignition events span a period of several milliseconds, and occur randomly in time (with no fixed frequency) prior to LBO. As the LBO limit is approached, more of these events occur in a given time period and thus the time between two such events decreases closer to LBO. Also the duration of the event, increases as the LBO limit is approached.

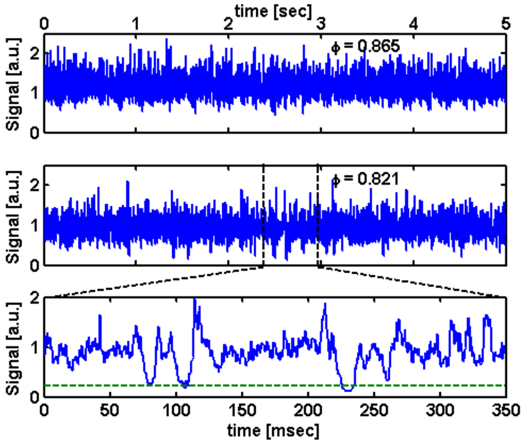

Figure 3. Time series data of OH chemiluminescence signal for ϕ = 0.865 and 0.821. (ϕ_{LBO} = 0.802) The expanded time series for the last case is also shown.

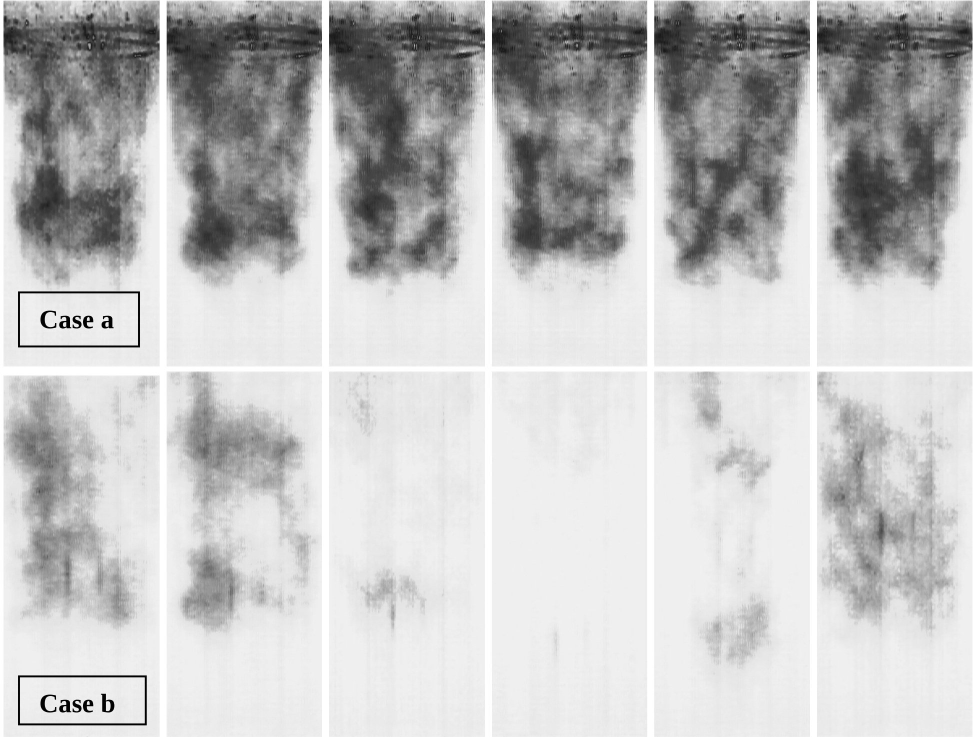

Figure 4. High speed visualization images (inverted grayscale). Case (a) ϕ = 0.79, time between images 2msec, case (b) ϕ = 0.76, time between images 16 msec showing a nearly total loss of flame followed by reignition (ϕ_{LBO} =0.745).

Detection method

Although various methods for identifying these events were proposed by Muruganandam *et. al* [4], threshold based detection is used in this work. Here we identify a precursor event whenever the OH signal drops below a (somewhat arbitrarily chosen) value equal to one-quarter of the mean signal value. This choice is based on the premise that the precursor signature is initiated by a local extinction event that temporarily lowers the chemiluminescence. Thus the low threshold approach provides the earliest detection of the event. The specific choice of threshold value for detection will vary depending on the combustor, the optical collection location, and the desired sensitivity and noise rejection of the technique. An example of noise effects is seen in Figure 5. During an extinction event, noise can cause the signal briefly rise above the event threshold and then fall below again.

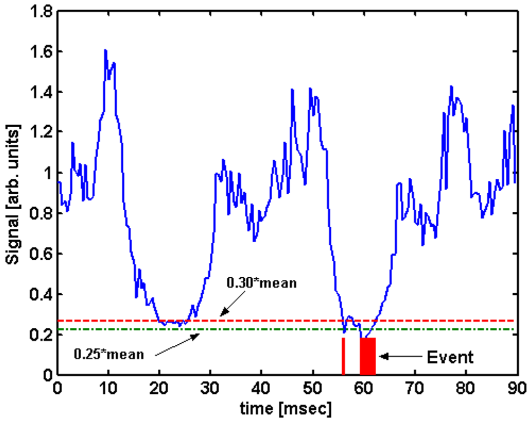

Figure 5. Noise rejection approach based on double thresholding used to detect the LBO precursor events. An event starts when the lower threshold is crossed and ends only when the upper threshold is crossed.

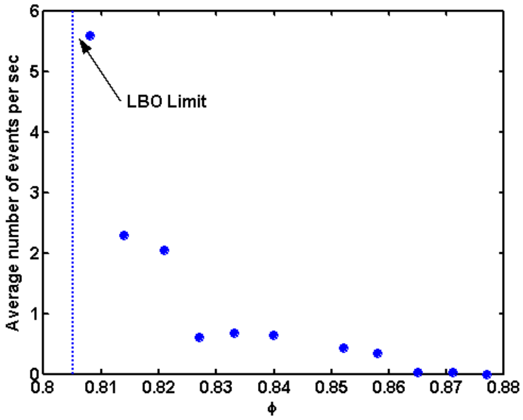

Figure 6. Variation of average number of events per second as a function of equivalence ratio. The dotted line indicates the LBO limit for these conditions.

To reduce the number of false alarms due to noise in the signal, double thresholding was used (see Figure 5). The event starts when the signal drops below a lower threshold, and ends only when the signal goes above the higher threshold. The gap between the two thresholds can be varied based on the noise present in the signal. Figure 6 shows the variation of average number of identified precursor events per second (averaged over 33 seconds) with equivalence ratio. Since this parameter increases as the LBO limit is approached, it can be used to sense the proximity to LBO.

LBO CONTROL ACTUATION

Options for control

There are various possible actions a control system could take to avoid LBO without changing the engine power setting. These include changing the swirl intensity, the relative amount of air introduced at the head end of the combustor (dome), the fuel distribution in the combustor or the inlet temperature. The primary goal in these actuation techniques is to provide an alternate stabilization mechanism for the flame or to increase the strength of the current stabilization point. In this study, the redistribution of the fuel inside of the combustor was chosen for its simplicity and practicality. The redistribution of the fuel in the combustor was accomplished by injecting a certain fraction of the fuel through a pilot injector located near the inlet of the combustor − the stabilization zone in this combustor.

Piloting Options

In the combustor employed, stabilization of the flame can be due to the central recirculation zone created by the swirl, the outer recirculation created by the dump plane, the bluff body in the center, or a combination of these. Figure 7 shows the different locations tested for injection of the pilot fuel. The central pilot injects the fuel into the inner recirculation zone, and thus might stabilize a flame anchored on it. It will, however, reduce the amount of recirculation in the central region by increasing the axial momentum there. The annular pilot injects fuel into the outer shear layer between the main premixed jet and the outer recirculation zone through a set of 8 holes along the perimeter of the primary jet. The radical and heat feedback from the enhanced recirculation zone could act as an anchor for the flame, by igniting the incoming mixture.

Tests showed that both central and annular pilots were not very effective unless the pilot split fraction was relatively high (no effect for pilot fuel less than ~12%). This was conjectured to be due to the movement of the recirculation zone due to the pilot jets, which might move the stabilization point in the combustor. Another possibility could be that the fuel injected mixes with the main flow so fast that by the time it reaches the flame zone, there is no effect of the piloting. Schlieren photography was used to study this mixing of these pilot jets with the main flow. This experiment was performed only in cold (nonreacting) conditions. The pilot fuel was replaced by helium and the main flow was air with similar flow rates as the combustor operating conditions. The schlieren images (Figure 8) show that the pilot fluid mixing is extremely rapid, supports the mixing argument.

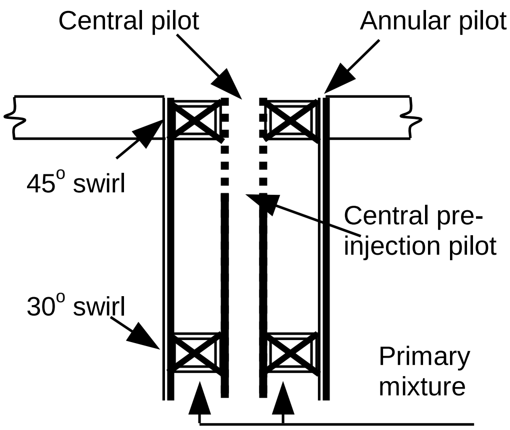

Figure 7. Schematic showing the various pilot options discussed. The central pre-injection pilot is the case used in the control experiments.

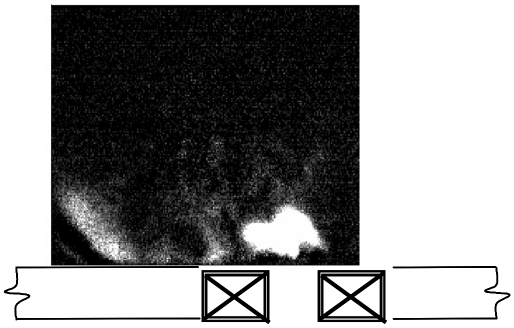

Figure 8. Schlieren image of the central pilot injected into cold flow. The jet does not penetrate more than one diameter into the combustor. Bright region at the left bottom corner of the image is an artifact of aberrations in the glass.

The pre-injection pilot is a modification of the central pilot, where the pilot tube is not inserted all the way up to the inlet of the combustor. By introducing the fuel ahead of the final swirler, it has some time to mix into the inner regions of the primary fuel/air mixture. The main, flame holding method in this case will most likely be swirl based, and injection of more fuel into the central recirculation zone might assist in stabilizing the flame. This pilot was found to be effective in decreasing the LBO limit for a pilot fuel fraction above ~5% of the total fuel flow. It was found that sending some air along with the pilot fuel was also necessary to produce successful piloting. This observation, although not investigated fully yet, could be due to the increased velocity of the pilot jet or the premixing. In this work, a constant fraction of the total air is sent through the pilot injector always, to maintain a nominally constant velocity field. The total fuel was kept constant while changing the fractional fuel through the central, pre-injection pilot.

Effect of pilot on LBO and LBO sensing

Since the pilot injection can change the dynamics of the combustor near the LBO limit or change 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 on the LBO limit for various pilot fuel fractions. As indicated by the vertical lines, the LBO limit moves to leaner mixtures with increasing piloting. The average number of events sensed per second as a function of equivalence ratio is also indicated for each pilot case. The same sensing approach described above successfully tracks the change in the LBO limit.

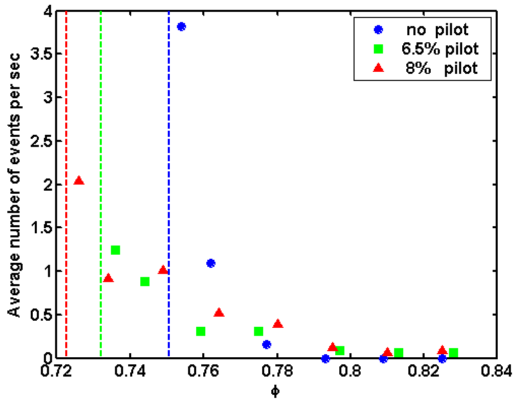

Figure 9. Average number of events per sec as a function of equivalence ratio for various pilot fractions, with nominally same velocity field. The dotted lines indicate the respective LBO limits for each case.

Effect of pilot on NOx

It was initially unclear how piloting would affect the NOx emissions from the combustor. Since the pilot introduces local regions of higher equivalence ratio, it might also increase the overall NOx. On the other hand, much of the combustion region has a lower equivalence ratio since part of the fuel has been redirected to the pilot. Also one must be careful in comparing NOx emissions from piloted and unpiloted combustor. Since the LBO limit for the piloted system is leaner, the piloted combustor allows operation at a lower overall equivalence ratio (and thus reduced NOx) without loss of safety.

Thus to compare NOx emissions for piloted and unpiloted conditions, the safety margin must be redefined. Our definition of safety margin for piloted conditions is the difference between the operating equivalence ratio and LBO limit for the same pilot fraction. This limit can be determined by a separate set of experiments where the nominal velocity field and the pilot split are kept constant and the overall fuel is decreased until LBO occurs.

A comparison of piloted and unpiloted cases is shown in Figure 10, which indicates the NOx index as a function of the safety margin. The overall equivalence ratio for the piloted case was maintained at the LBO limit of the unpiloted combustor. It should be noted that NOx decreases with a decrease in pilot split fraction, but this also decreases the safety margin. Also, it can be seen that piloted combustor has a lower NOx index compared to zero-pilot combustor *for the same safety margin*. For example at a safety margin of 0.04 (6.5% pilot fraction), the NOx index is reduced by 25% compared to the unpiloted case.

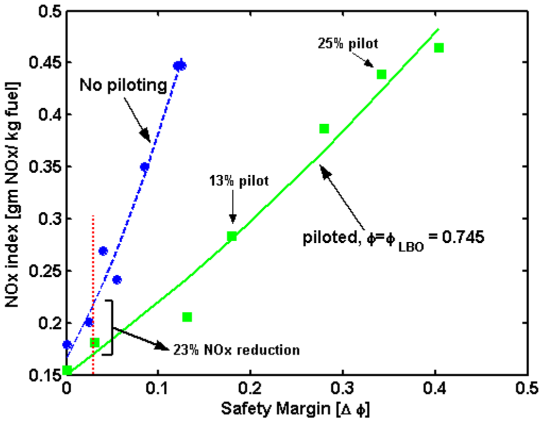

Figure 10. NOx as a function of safety margin for piloted and unpiloted operation of the combustor.

LBO CONTROL

The observations so far can be summarized as follows. There are precursor events occurring at random times before the LBO and they can be detected by observing the optical emissions from the combustor. Piloting increases the stability of the flame in the combustor and thus moves the LBO equivalence ratio limit to leaner values. Thus there is a gain in safety margin by increasing the pilot fraction. But this increases the NOx emissions, and thus there is an optimum to be reached between these conflicting factors. This section describes the control methods used to operate the digital solenoid valves in order to rapidly control the fuel split, the control algorithm and tuning employed to optimize the combustor operation, and results of the combustor under closed-loop control.

Fuel valve control

Control authority is available over the ratio between the pilot and main fuel via the valve manifold. The miniature solenoid valve manifold was operated in PWM (pulse width modulated) mode at 25 Hz. The opening and closing times of the valves, induced a cutoff and saturation, respectively, in the response to a commanded duty cycle signal. To mitigate the undesired effects due to valve opening and closing delays, the PWM command was increased by the appropriate valve response times and the command was distributed among two valves such that no single valve had to operate at over 50% duty cycle. The opening and closing times were both found to be 1% of the PWM period, or 0.4 milliseconds. Therefore, a command to open 2.9 valves results in two completely open valves, one valve receiving a 51% duty cycle command (and outputting 50% duty cycle due to opening time response), and a second valve receiving a 41% duty cycle command (and outputting 40%). The command signal resolution is 1% duty cycle (valve control parameter), and with the ten valve setup, varied from 0% to 1000%, with each 100% corresponding to another fully open valve.

Control algorithm

The OH chemiluminescence signal serves as the feedback signal to determine the proper pilot fuel split. In the absence of LBO precursors, the pilot fuel fraction is steadily decreased. When precursors are detected, the control system responds by increasing the pilot fuel fraction. After this correction, if no other precursors are detected, the system again tries to lower the pilot fuel fraction in order to minimize NOx.

The control algorithm has to account for a sensor signal that is subject to both drift and noise. The signal drift is mainly due to equivalence ratio change and is a slow phenomenon. By contrast, the blowout precursors cause a brief, abrupt drop in the signal level. To calibrate for drift, the signal mean value was constantly updated based on the data from a fixed (previous) time window. As noted previously, two threshold levels were used: one for event start, one for event end. This allows for better noise rejection, and can be customized to suit specific combustors. Also, the threshold levels are based on a fraction of the recent mean signal in order to account for long term changes in the system, and to adapt to changes in operating power.

Control actuation is based on an alarm flag, as seen in Figure 11. An 'alarm' is declared whenever the lower threshold is crossed, and an event is initiated. If more than a maximum allowable number of alarms occurs within a fixed (previous) time window, the valve parameter is increased. This effectively results in opening a fraction of a valve. If no further alarms occur during a preset duration (based on a timer elapsing), the valve parameter is decreased, effectively closing a fraction of a valve.

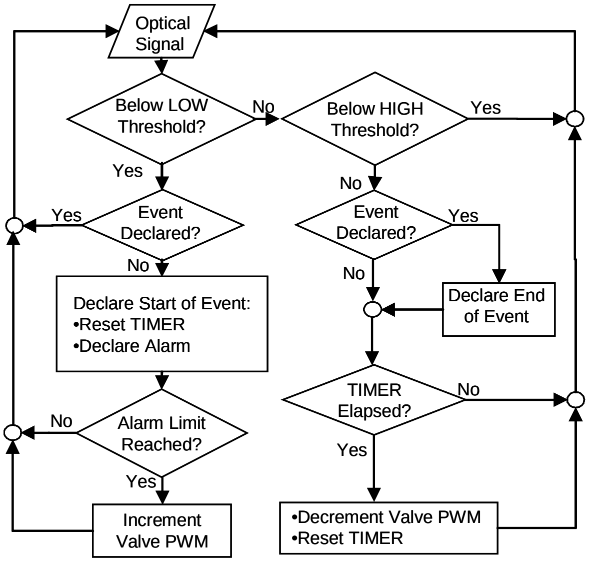

Figure 11. Algorithm followed by the controller.

Control Tuning

System tuning involves manipulation of the control parameters to achieve an ideal tradeoff between sensitivity and response time. Both the signal mean and the alarm count are updated based on samples and threshold crossings over the time window, 1 second in the current tests. Increasing the time window for the mean signal would increase the system susceptibility to drift. Similarly, changing the window for the alarm counts or maximum allowed alarms in the window would effect the system sensitivity (and therefore the safety margin and noise rejection) and time response of the system. The threshold levels and the valve parameter increment and decrement (effectively the incremental changes in the pilot fraction during each update cycle) also determine the system sensitivity. The timer duration, which is the amount of time the controller waits before decrementing the valve parameter also contributes to the system response time.

An effective loop gain may be described as a combination of parameters that lead to greater system response. One effective gain can be used to describe the decrement logic, or the left side of logic flowchart, and another may be used to describe the increment logic, or the right side of the flowchart. The timer duration and decrement step value contribute to the decrement gain, while the alarm limit and increment step value contribute to the increment gain. While the decrement occurs steadily, the increment has to be more severe and instantaneous to avoid a blowout. Therefore, the PWM decrement loop pushing the system towards minimum pilot fuel split is tempered by a longer timer duration and smaller PWM steps, both of which lower the effective decrement gain. The alarm response loop, by contrast, has a higher effective gain with a low alarm limit and a larger valve command.

Closed-loop control results

The control system was tested under two cases: one where the operating conditions were nominally steady and a second case where the air flow rate was independently varied. For both cases, the time window was set to 1 second, and the threshold levels were set at 35% and 40% of the mean signal. In addition, the maximum number of alarms allowed before the system begins to increase the pilot fuel was two (in the 1 second window).

To test the behavior of the controller at constant conditions, an experiment was conducted at an overall equivalence ratio that would result in blowout without any pilot fuel. Therefore, the system was started (before the controller was turned on) with two valves open. It can be seen from Figure 12 that the controller eventually attains a nearly stationary condition. The minimum allowable pilot fraction appears to be 14% based on the effective safety margin set by the chosen controller parameters. Since extinction precursors do occur somewhat randomly and because the controller always tries to keep lowering the pilot fraction in the absence of alarms, the system drifts between the minimum pilot fraction and a higher value of ~18%.

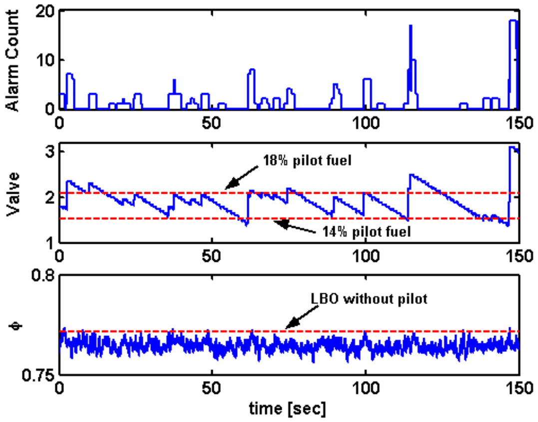

Figure 12. Response of the integrated control system to nominally stationary operating conditions.

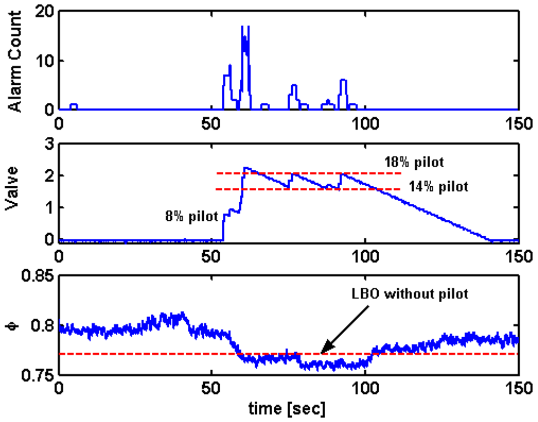

Figure 13. Response of the integrated control system to varying operating conditions.

Figure 13 shows the behavior of the closed-loop system when there are fluctuations in the operating conditions. In this case, the starting conditions were chosen such that the combustor was stable without piloting. The air flow was manually varied, with the overall equivalence ratio changed at a maximum rate of 0.03 sec^{-1}. It can be seen that the controller did not take action until the LBO limit was approached (at t≅54s). It successfully suppressed blowout by turning on the pilot. For $60<t<100$ s, when the combustor was below the unpiloted LBO limit but the air flow was essentially constant, the system operated in a nearly stationary mode. When the air was finally decreased to a point where the equivalence ratio was no longer below the unpiloted LBO limit, the controller eventually diverted all the fuel back to the main flow. The relatively slow response of the system in decreasing the pilot is due to the very conservative set of valve decrement parameters chosen. These values have not been optimized.

SUMMARY AND CONCLUSIONS

A complete active control system: sensing, actuation and control algorithm, has been developed to prevent LBO in gas turbine combustors, and was demonstrated in a premixed, atmospheric-pressure model combustor. The system is designed to minimize NOx by ensuring safe operation at lean equivalence ratios. The system was effective in operating the combustor at a reduced NOx index by reducing the allowable equivalence ratio in the reaction region of the combustor.

The approach of lean blowout (LBO) is detected by monitoring OH chemiluminescence with an optical fiber and a rugged, remotely located, sensor. A sudden and dramatic drop in OH signal represents a local extinction of the flame. An LBO precursor event is defined to begin when the OH signal drops below a threshold level equal to some fraction of the recent mean signal and to end when it rises above another threshold level. The apparently random precursor events occur more frequently as the LBO limit is approached.

The system employs a small pilot fuel injector, and controls the fraction of total fuel injected through the pilot. This allows control at a fixed power setting. When precursors are detected, the fuel is redistributed to the pilot to increase the equivalence ratio in the flame stabilization zones. Among various piloting approaches investigated, a central pre-injection pilot was found to work best. This pilot decreased the LBO limit (based on overall equivalence ratio) for pilot fractions as low as 5%. The LBO precursor sensing successfully tracked the increase in LBO margin with increasing pilot fraction. The NOx index of the combustor emissions increases with increased pilot fraction. When compared with the NOx emissions from the pilotless combustor *at the same safety margin*, however, the NOx index decreased (23% at 0.04 margin). Thus the piloting approach can decrease NOx emissions without compromising performance.

An effective system controller was developed for closed loop control. The controller increases the pilot fuel fraction when a given number of events are detected in a fixed time window. When there are fewer events, the controller decreases the pilot fraction in order to decrease the NOx emissions without changing the power setting. Various control parameters including the sensitivity of the sensor (the threshold values), the rate of decrease of the piloting, the response of the controller to the precursors and the time window can be tailored to a specific combustor. In closed loop operation, the system successfully minimized the NOx index of the combustor without permitting LBO to occur. The system was also able to respond successfully as the overall operating conditions were varied. The system prevented lean blowout, while minimizing the pilot fuel, and therefore also minimizing the NOx.

Since practical turbine engines combustors operate at a range of pressures, it will be important to investigate the LBO control at both lower and higher pressures. Also, this approach to LBO control should be extended to liquid fueled (and nonpremixed) combustors. This will likely require modifications in the actuation approach. Further investigation into control schemes would likely encompass some form of derivative control, whereby the alarm rate is also used to determine the amount of command input to the valves, and the number of alarms over an extended duration could be used to vary the rates of decrease or increase of the valve command.

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REFERENCES

[1]Nicholson, H., and Field, J., "Some Experimental Techniques for the Investigation of Mechanism of Flame Stabilization in the Wakes of Bluff bodies", Third Symposium (international) on Combustion, 1951.

[2]Chao, Y.C., Chang, Y.L., Wu, C.Y., and Cheng, T.S., "An Experimental Investigation of the Blowout Process of a Jet Flame", Twenty Eighth Symposium (International) on Combustion, 2000.

[3]Hedman, P.O., Fletcher, T.H., Graham, S.G., Timothy, G.W., Flores, D.V., and Haslam, J.K., "Observations of Flame Behavior in a Laboratory-Scale Pre-mixed Natural Gas/Air Gas Turbine Combustor from PLIF measurements of OH", Paper No. GT-2002-30052, *Proceedings of ASME TURBO EXPO 2002*, Jun 3-6, Amsterdam, Netherlands, 2002.

[4]Muruganandam, T. M., Nair, S., Neumeier, Y., Lieuwen, T.C., Seitzman, J.M., "Optical And Acoustic Sensing Of Lean Blowout Precursors", *AIAA 2002-3732*, 38th AIAA Joint Propulsion Conference, July 2002.

[5]Gupta, A.K., Lilley, D.G., and Syred, N., "Swirl Flows", Abacus Press, Kent, England, 1984.

[6]Gaydon, A.G. and Wolfhard, H.G., "Flames: Their Structure, Radiation, and Temperature", Fourth edition, Chapman and Hall, 1978.

[7]Lawn, C.J., "Distributions of Instantaneous Heat Release by the Cross-Correlation of Chemiluminescent Emissions," *Combustion and Flame*, Vol. 132, 2000, pp. 227-240.

[8]Roby, R.J., Hamer, A.J., Johnsson, E.L., Tilstra, S.A., and Burt, T.J., "Improved Method for Flame Detection in Combustion Turbines", *Transactions of the ASME*, Vol. 117, 1995, pp. 332 –340.

[9]Mehta, G.K., Ramachandra, M.K., and Strahle, W.C., "Correlations between Light Emission, Acoustic Emission and Ion Density in Premixed Turbulent Flames", *Eighteenth Symposium (International) on Combustion,* 1981, pp 1051-1059.

[10]Roby, R. J., Reaney, J .E., and Johnsson, E. L., "Detection of Temperature and Equivalence Ratio in Turbulent Premixed Flames Using Chemiluminescence," Proceedings of the 1998 Int. Joint Power Generation Conference, Vol. 1, 1998, pp. 593-602.

[11] Morrell, R., Seitzman, J., Wilensky, M., Lee, J., Lubarsky, E., and Zinn, B., "Interpretation Of Optical Flame Emissions For Sensors In Liquid-Fueled Combustors," paper AIAA-2001-0787 at the 39th AIAA Aerospace Sciences Meeting, Reno, NV, January 8-11, 2001.