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# Active Control of Lean Blowout for Turbine Engine Combustors

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**A complete, active control system has been developed to permit turbine engine combustors to operate safely closer to the lean-blowout (LBO) limit, even in the presence of disturbances. The system uses OH chemiluminescence and a threshold-based identification strategy to detect LBO precursor events. These nonperiodic events 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 event-based 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 those from the unpiloted combustor operating at the same safety margin and same nominal velocity field. The controller minimizes the $NO_x$ at constant total power by keeping the pilot fuel fraction at the lowest value needed to limit the number of precursor events to an acceptable level.**

## Introduction

THE desire for power and propulsion systems with reduced environmental impact has motivated interest in reducing pollutant emissions while maintaining (or improving) efficiency, reliability, and performance. This demand for low pollutant emissions has increasingly driven engine developers to consider combustors that primarily operate under fuel-lean conditions. For example, premixed natural gas combustors have demonstrated the capability to greatly reduce $NO_x$ emissions in ground power generation.[1,2] A similar potential for improvement exists for liquid-fueled combustors, for example, using lean premixed, prevaporized approaches or lean direct injection. Even for current aeroengine combustors, which operate in a partially premixed mode with rapid mixing after fuel injection, increased fuel-lean operation can lead to lower $NO_x$ k 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, for example, 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 shutdown and relight procedure, in addition to loss of power during this period.

Currently, stable performance is ensured by operating the combustor with an ample safety margin above the LBO limit, for example, at a higher equivalence ratio $\phi$. However, the $\phi$ at which LBO occurs (the LBO limit) is not a fixed value; it varies with a number of operating conditions, including the velocity field and turbulence levels in the combustor, the inlet air temperature profile, the combustor wall temperature distribution, and the combustor pressure. Because it is hard to monitor all of the important parameters, the LBO limit for some smaller sets of parameters can be considered an uncertain value. This is one reason an ample safety margin is required. For the purposes of this work, safety margin from LBO at a given velocity field is defined as the difference in $\phi$ between the operating condition and the LBO limit for the same nominal velocity field, inlet temperature, and combustor pressure. Reduced $NO_x$ emissions could be obtained by reducing the LBO margin, if safe operation could be ensured by some other means.

The remainder of this paper describes an approach for ensuring safety near LBO through the use of an active control system. It describes a method for detecting LBO precursors, a controllable means for improving flame stability when LBO is imminent, and the design of a controller. Also included are descriptions of the experimental hardware used to demonstrate active LBO control and performance results for the components and the complete control system.

## Background

A number of specific characteristics of flame behavior associated with lean flame stability have been studied by researchers. For example, Nicholson and Field[5] 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.[6] observed similar phenomenon in a nonpremixed, turbulent jet flame during the blowoff process. They reported that prior to blowoff 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.[7] imaged the OH radical distribution in a premixed natural gas/air combustor using planar laser-induced fluorescence. 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. Other researchers have also observed fluctuations or transient behavior very close to blowout.[8–11] Thus, it seems that flames transition from stable combustion to LBO through a transient regime that manifests itself through large-scale unsteadiness and, most likely, local variations in heat release.

This transitional behavior, which appears to precede flame loss, opens an avenue for active control of LBO in combustors. If this transitional behavior sufficiently precedes the onset of blowout,

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then there is the possibility of detecting precursors to LBO. An active control system that monitors the precursors could allow an engine to operate safely at a fuel–air ratio closer to the LBO limit, as compared to present engine combustors. This would permit reduced $NO_x$ emissions without loss of safety. Because the primary operator input is typically engine power level, that is, fuel flow rate, it is important that such a control system would be able to increase the stability of the combustion process at a fixed power setting.

### Observables and Detection

As just noted, the transitional behavior that precedes blowoff suggests that LBO precursors can be detected by sensing the transient heat-release processes within the combustor. To ensure robustness in the harsh environment of the engine, it is desirable to observe these processes with a nonintrusive sensor that can be located outside the high-pressure, high-temperature combustor. This nonintrusive requirement combined with system simplicity leads to two main sensing options: detection of electromagnetic or acoustic radiation produced from within the combustor.

Although 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 gas molecules that are produced by the chemical reactions and that can relax to lower energy states by emitting light. Because the intensity of emission is generally proportional to the chemical production rate of the excited molecule, the chemiluminescence intensity can be related to chemical reaction rates.[12] For this reason, chemiluminescence has been used previously as a rough measure of heat-release rate and even equivalence ratio.[13−17]

Because chemiluminescence is directly related to chemical reaction rates, it can provide information on the presence and strength of the combustion process in a specific region of the combustor. Also, it inherently has a fast time response providing fast detection of flame instability events. Therefore, optical detection of chemiluminescence is especially appropriate for monitoring transient combustion events in portions of the combustor that might first experience the transient events that precede LBO. Finally, optical sensing in general is applicable to a combustor, for example, using fiber-optic ports on the combustor walls.

An alternate approach to optical sensing is detection of acoustic radiation emitted by the combustion process. Specifically unsteady heat release causes transient regions of volume expansion in the combustor, and these regions are therefore sources of acoustic radiation. Both chemiluminescence (optical) and acoustic pressure measurements have been used for detection of specific LBO precursor events by Muruganandam et al.[18] In the present work, the optical approach is employed.

The primary chemiluminescent species of interest in a hydrocarbon flame are electronically excited OH, CH, and $C_2$ radicals and $CO_2$. In lean hydrocarbon flames, OH tends to be the strongest narrowband 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.[16,17] Thus this work uses the stronger chemiluminescence from OH (near 308 nm) for detecting lean blowout. The ultraviolet OH chemiluminescence emission also has less interference from wall or particle radiation as compared to the visible chemiluminescence from CH and $C_2$, as blackbody radiation peaks in the infrared for combustor operating temperatures.

### Control Actuation

An ideal LBO active control system should be capable of preventing LBO without altering the engine power, that is, the fuel consumption rate. There are various possible actions a control system could take to avoid LBO without changing the engine power setting. This includes changing the flowfield, for example, by changing the swirl intensity, to increase the residence time of the combusting gases and enhance mixing of fuel and air with hot products. In addition, one could provide external energy via electrical, thermal, or electromagnetic sources to increase local chemical reaction rates. The latter can also be achieved by changing the local $\phi$ (to less lean mixtures) without changing the overall fuel consumption rate.

The primary goal in all of these actuation techniques is to provide an alternate stabilization mechanism for the flame or to increase the effectiveness of the existing stabilization mechanism. In this study, redistribution of the fuel within the combustor was chosen for its simplicity and practicality. For example, fuel redistribution has been used to suppress combustion instabilities in commercial, aeroderivative engines.[19] Here, the redistribution of the fuel is 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.

### Controller

Active control systems for gas turbines have focused mainly on controlling combustion instabilities, not LBO prevention.[19,20] LBO prevention has been demonstrated with the use of predetermined models of engine performance to infer LBO conditions and a rule-based control algorithm.[19] An ideal control system for LBO prevention would act only when the combustor is truly operating near LBO. As already indicated, there is evidence that LBO precursor events can be detected. Thus, a control algorithm that can assess the stability of the combustor based on some analysis of the precursor events is required. As the stability of the combustor decreases, the controller will actuate the alternate stabilization mechanism, for example, pilot fuel. Thus, the challenge is to design an event-based control algorithm that accurately identifies incipient LBO conditions and responds rapidly to prevent LBO. For improved $NO_x$ performance, the control system could also use $NO_x$ emission from the combustor as an input and can optimize the LBO stability and the $NO_x$ emissions from the combustor.

## Experimental

### Combustor

The experiments were performed in an atmospheric pressure, premixed, swirl-stabilized dump combustor (Fig. 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 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 deg followed by 45 deg causing the exit flow to have a (theoretical) swirl number of 0.66 (Ref. 21). 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 UV radiation. A rectangular section glass tube was also available for schlieren imaging studies of mixing in the combustor. At the flow rates used here, the average power density in the combustor is $\sim$100 MW/m$^3$.

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

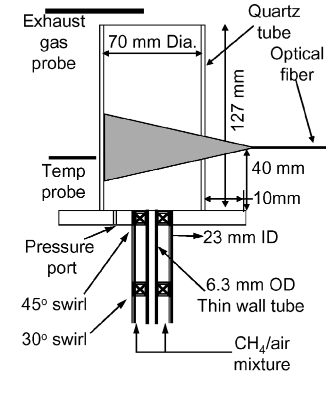


**Fig. 1 Combustor schematic showing the viewing area for the optical fiber used.**

product gases would be ~20 m/s. The LBO limit of the combustor varies between ~0.75–0.80, depending, for example, on the combustor flow rate and ambient conditions. A thermocouple was used to monitor the change in the temperature of the combustor wall, as this by itself can cause the LBO limit to change. For most cases presented here, the external wall temperature was in the range 400–500 K. The combustor exhaust gases were sampled with a suction probe located just inside the combustor exit plane, which could be adjusted to different radial and azimuthal locations. The exhaust composition ($CO_2$, CO, $O_2$, and $NO_x$) was analyzed with a commercial gas analyzer (Land Instruments International, Ltd., LANCOM series II). According to the manufacturer, this system has an accuracy of ±1 ppm for the NO and CO measurements.

**Optical Setup**

The imaging region for the chemiluminescence collection optics setup is also illustrated in Fig. 1. The optical collection setup employed a 365-$\mu$m-diameter fused silica optical fiber, with an acceptance-cone half-angle of about 12 deg. The collected radiation passed through an interference filter, centered at 308 nm (full-width half-maximum of 10 nm), which corresponds to the OH $A^2\Sigma$-$X^2\Pi$ transition. The collected OH emission was detected by a miniature, metal package PMT (Hamamatsu H5784-04), with a built-in amplifier (bandwidth of 20 kHz) to convert the current to voltage and operates from a 12-V dc source.

To help understand the combustor behavior, a high-speed intensified charge-coupled-device 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 $\mu$s. 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 flow control system had both manual valves and miniature control valves. For open-loop control experiments, manual valves were used, and the flow rates were monitored using calibrated rotameters. The flow control and monitoring system had a resolution that is equivalent to a change in $\phi$ of approximately 0.003. The flow system included an orifice meter on the airline to monitor the airflow rate during the closed-loop tests. Closed-loop control experiments employed a set of 10 miniature solenoid valves (AM1124, Asco Scientific). These two-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 5-V signal from the control computer, which activated a set of relays to switch these valves at 24 V. The valves were connected in parallel in a central manifold.

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 I/O boards (PowerDAQ PD2-MF-64 and PD2-AO-32, United Electronic Industries, Inc.).

## LBO Sensing Results

**LBO Precursor Events**

Experiments were conducted at various $\phi$ near the LBO limit. Chemiluminescence signals from the combustor showed intermittent events occurring very close to LBO. Figure 2 shows examples of optical sensor outputs at a stable $\phi$ and one near LBO. In both cases, the signal has significant high-frequency fluctuations expected from turbulent combustion. Overall, the mean OH chemiluminescence signal decreases as the fuel is reduced. More importantly as the LBO limit is approached, a number of sudden deep reductions in the OH emission are observed. These drops in signal are larger on both absolute and relative scale (compared to the mean) for the lower $\phi$ case. These sudden drops in OH chemiluminescence are interpreted as temporary extinction events within the combustor. 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.

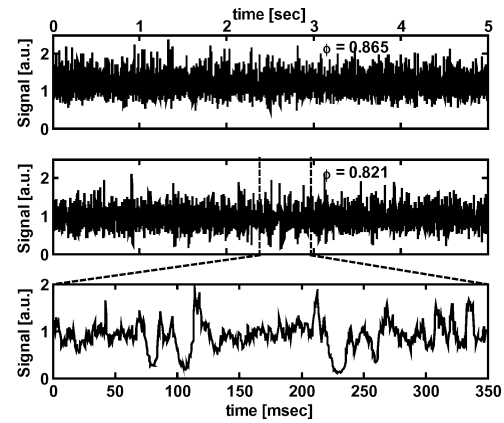


**Fig. 2 Time-series data of OH chemiluminescence signal for equivalence ratio $\phi = 0.865$ and 0.821 ($\phi_{LBO} = 0.802$). The expanded time series for the last case is also shown.**

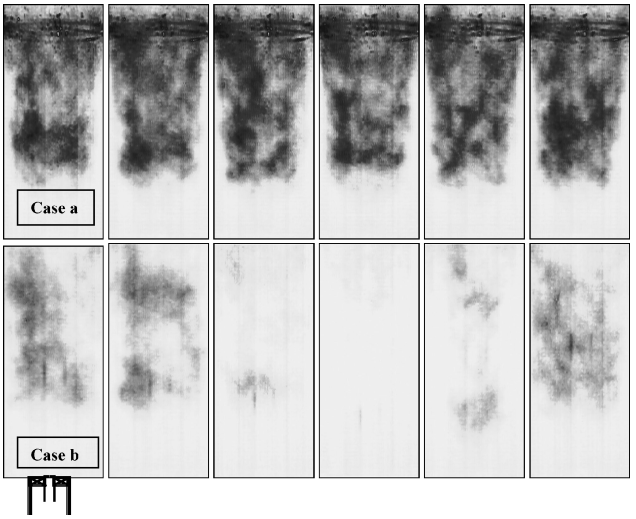


**Fig. 3 High-speed visualization images (inverted grayscale): case a, equivalence ratio $\phi = 0.79$, time between images 2 ms; and case b, $\phi = 0.76$, time between images 16 ms showing a nearly total loss of flame followed by reignition ($\phi_{LBO} = 0.745$). The location of the combustor inlet is indicated in the first image of case b.**

A closer investigation of these events using high-speed visualization (Fig. 3) shows that there are instances when the visible flame emission in a large part of the combustor drops drastically for a short duration and then reappears ("reignites"). The flame, when it reappears, is temporarily more intense. The flame appears to go through a regular (more stable) combustion process, until the next event occurs. Although the frames corresponding to the extinction events appear to indicate the absence of any combustion, it appears from the OH chemiluminescence signal (Fig. 2) that during these events there is still a weak flame that is below the sensitivity levels of the camera. It is the regions of weak combustion and high-temperature products that are the likely sources of the reignition. The individual large extinction and reignition events each span a period of several milliseconds, and they occur randomly in time (i.e., no noticeable periodicity) before 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. For the control experiments, the fiber-optic collection volume was placed such that it collected light from the brighter part of the central recirculation zone, which is believed to be the main stabilization region. Although the actual flame stabilization might be a little lower than this region, the signal levels from that region are weak, and the signal-to-noise ratio is poor.

### Detection Method

Various methods for identifying these precursor events have been proposed by Muruganandam et al.[18] Here, we employ threshold-based detection. In this approach, a precursor event is defined to begin whenever the OH signal drops below some threshold value, for example, 25% of the recent mean OH signal. The reasoning behind this approach is 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. Although the optimal choice of threshold value for detection can vary depending on the combustor design, the sensing volume, and the desired sensitivity and noise rejection of the technique, this approach is robust and should not require significant tuning for individual engines. An example of noise effects is seen in Fig. 4. During an extinction event, fluctuations in the combustor heat release can cause the signal to briefly rise above the event threshold and then fall below again. There can also be flame movement in and out of the collection volume, or the flame can extinguish locally as expected from turbulent combustion.

To reduce the number of false alarms caused by noise in the signal, double thresholding was used here (see Fig. 4). An event starts when the signal drops below the 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 5 shows the variation of average number of identified precursor events per second (averaged over 33 s) with $\phi$. Because this parameter increases as the LBO limit is approached, it can be used to sense the proximity to LBO. Alternately, one can also use the average duration between the events (which decreases near LBO) or the average duration spent below the threshold (which increases near LBO) as an indicator of the proximity to LBO.[18]

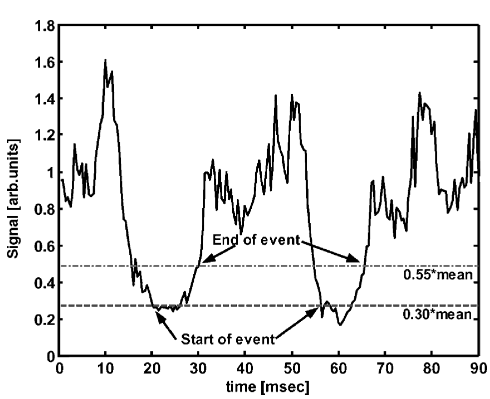


**Fig. 4 Noise rejection approach based on double thresholding used to detect the LBO precursor events. An event starts when the lower threshold is crossed and ends only when the upper threshold is crossed. Two precursor events are shown here.**

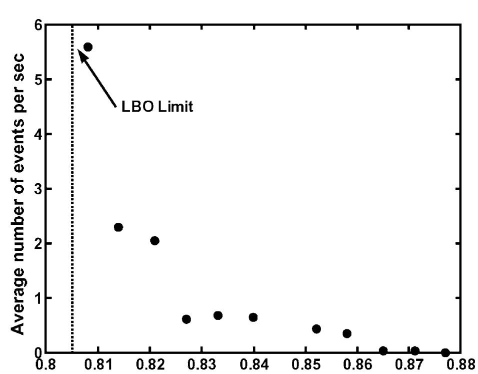


**Fig. 5 Variation of average number of events per second as a function of equivalence ratio: · · · ·, LBO limit for these conditions.**

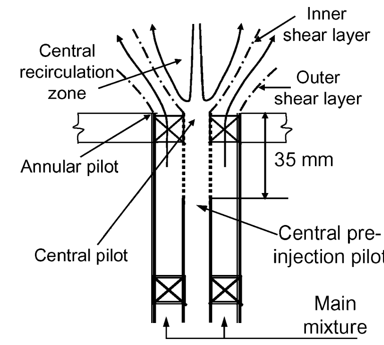


**Fig. 6 Schematic showing the various pilot options discussed. The central preinjection pilot is the case used in the control experiments.**

## LBO Control Actuation

### Piloting Options

Control actuation through piloting is intended to provide better stabilization near the nominal LBO limit. Because the primary goal of this work was to demonstrate the feasibility of active LBO control, rather than develop an optimal and universal piloting approach, we investigated several piloting approaches in order to find a method that provided control authority in our system. In the current combustor (see Fig. 6), the flame is stabilized by a combination of the central recirculation zone created by the swirl, the outer recirculation created by the dump plane, the shear layers and the bluff-body recirculation at the center of the inlet. Three pilot fuel-injection locations were investigated. The central pilot injects the fuel into the inner recirculation zone and thus could stabilize a flame anchored 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 eight 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 effective unless the pilot split fraction was relatively high (pilot fuel fractions ~12%). The reason for the ineffective annular pilot might be that the primary stabilization for this combustor is the inner recirculation zone or the inner shear layer (see Fig. 6). The poor response of the central pilot might be caused by its influence on the inner recirculation zone, with the momentum of the pilot jets altering the stabilization point in the combustor. Another possibility is fuel–air mixing; if the pilot fuel mixes with the inner recirculation zone and not significantly with the inner shear layer, there might not be an enhancement of stabilization of the flame.

The third approach, central preinjection pilot, is a modification of the central pilot method. In this case, the pilot tube is not inserted all of the way up to the inlet of the combustor. By introducing the fuel slightly upstream of the final swirler, it has some time to mix into the inner regions of the primary fuel/air mixture. It also has less impact on the velocity in the inner recirculation zone. The primary flame-holding mechanism in this case would most likely be the inner recirculation zone and the inner shear layer, and injection of more fuel into both of these zones 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. Although this air requirement was not thoroughly investigated, possible causes are the need to control the shear between the pilot tube flow and the primary flow and the need to get a fuel–air ratio in the stabilization region closer to stoichiometric. In the results reported next, a constant fraction of the total air was sent through the pilot injector always, to maintain a nominally constant velocity field.

### Flow Control System

The schematic of the flow system is shown in Fig. 7. Both fuel and air lines were double choked before the split between main and pilot

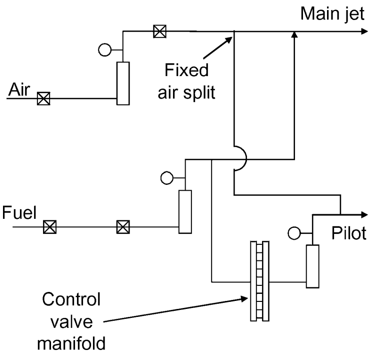


**Fig. 7 Schematic of the flow system showing the fuel split and the control valve manifold.**

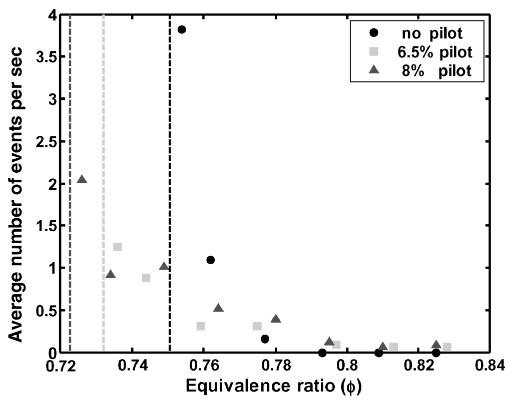


**Fig. 8 Average number of events per second as a function of equivalence ratio for various pilot fractions, with nominally same velocity field: - - - -, respective LBO limits for each case.**

lines, and thus the total flow rate could be maintained at a constant value throughout the experiment. The split between the pilot air and the primary air was fixed at a constant value throughout this study. The airflow was adjusted manually and was kept constant throughout each run except for the closed-loop control experiments discussed later. The total fuel flow rate was also manually adjusted and was maintained constant throughout each run. During the closed-loop testing, the pilot split fraction was controlled using the manifold of 10, computer-controlled, parallel solenoid valves. An increased fraction of fuel flow through the pilot was attained by increasing the number of open valves, or the amount of time that the valves were open.

#### LBO Sensing and Open-Loop Control

Because the pilot injection can change the combustor dynamics near the LBO limit and the spatial extent of the active combustion region, it could influence the efficacy of the LBO precursor sensing. Thus, the sensing technique was reinvestigated during open-loop tests of the pilot fuel actuation. Figure 8 shows the results for the threshold-based, event detection strategy for various pilot fuel fractions, as well as the observed changes in LBO limit. As indicated by the vertical lines, the LBO limit moves to leaner (overall) mixtures with increased pilot fraction. The average number of events sensed per second as a function of $\phi$ is also indicated for each pilot case. Clearly, the sensing approach is sufficiently robust to track successfully the changes in the LBO limit because of pilot staging.

#### $NO_x$

It was initially unclear how piloting would affect the $NO_x$ emissions from the combustor. Because the pilot fuel injection introduces local regions of higher $\phi$ and thus higher local temperature, it is conceivable that this would increase the overall $NO_x$ emissions from the combustor. On the other hand, much of the combustion region has a lower $\phi$ because part of the fuel has been redirected to the pilot. Also one must define a fair basis for comparing $NO_x$ emissions from the piloted and unpiloted combustor. Because the LBO limit for the piloted system is shifted to leaner mixtures, the piloted combustor can operate safely at a lower overall $\phi$ and hopefully with reduced $NO_x$.

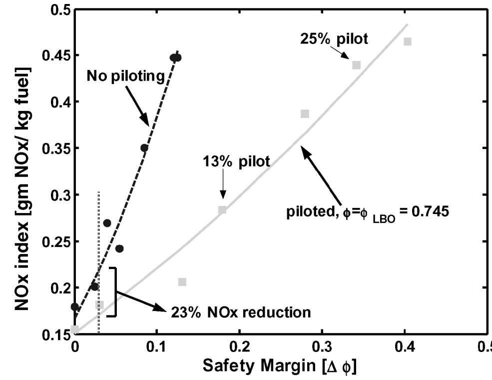


**Fig. 9 $NO_x$ emission index (EI $NO_x$) as a function of safety margin (in terms of difference in equivalence ratio $\phi$) for piloted and unpiloted operation of the combustor.**

From an operational viewpoint, it is useful to compare $NO_x$ emissions for piloted and unpiloted conditions at a fixed safety margin. As defined earlier, the unpiloted LBO safety margin is the difference in $\phi$ between the operating condition and the LBO limit for the same nominal velocity field, inlet temperature, and combustor pressure. Our definition of safety margin for piloted conditions is the difference between the operating $\phi$ and the LBO limit for the same pilot fraction. This piloted LBO limit is 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 Fig. 9, which depicts the dry $NO_x$ emission index (EI $NO_x$) as a function of the safety margin. The measurements were made in the center of the exit plane. Measurements with the probe located at other locations indicated that the gas compositions were nearly uniform at the exit plane for the various operating conditions. The overall $\phi$ for the piloted case was maintained at the LBO limit of the unpiloted combustor. $NO_x$ 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 $NO_x$ 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 $NO_x$ index is reduced by 23% compared to the unpiloted case. A similar result has been observed in turbulent, premixed, coflow flames.[22]

## LBO Control

The results so far can be summarized as follows. There are nonperiodic precursor events that occur before the LBO condition is reached, and they can be detected by observing the optical emissions (chemiluminescence) from the combustion zone. Piloting increases the stability of the flame in the combustor and thus moves the LBO limit to leaner equivalence ratios. Thus, there is an increase in safety margin for higher pilot fuel fractions. Increasing the pilot fuel fraction, however, increases the $NO_x$ emissions. Thus there is a tradeoff between stability (operational safety) and $NO_x$ emissions (human and environmental safety). This tradeoff can be continuously balanced by an active control system. This section describes the control methods used 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.

#### Control Algorithm

In the current setup, control authority is available over the fraction of total fuel distributed to the pilot. The OH chemiluminescence signal provides the feedback necessary to control the pilot/main fuel split fraction. The control algorithm is an event-based control in which the absence of LBO precursors leads to the decrease of pilot fuel fraction to minimize $NO_x$. When LBO proximity is detected, the control system responds by increasing the pilot fuel fraction. The main objective of the control algorithm is to maintain the pilot split

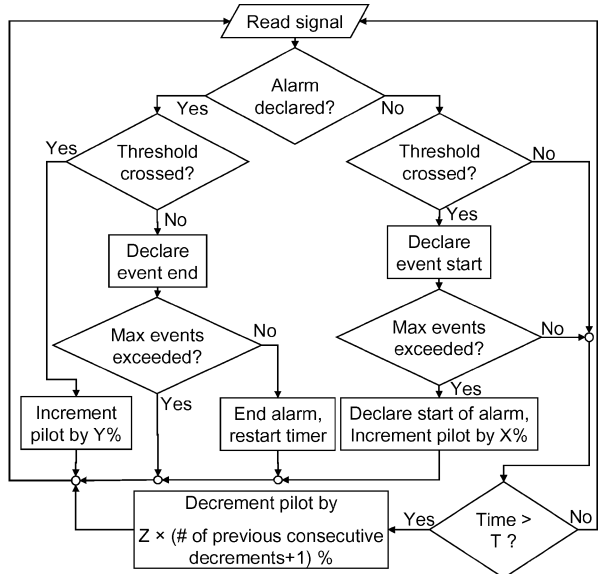


**Fig. 10 Control algorithm: TIMER tracks the time since the last event. If no events occur in the time limit, the pilot fraction is decreased.**

fraction at a minimum while maintaining operational stability. In this arrangement, the controller has no input about any flow conditions (fuel or airflow rates, pressure, etc.) in the combustor, except for the precursor detection.

Control actuation is based on the number of precursor events detected in a time window, as seen in Fig. 10. An alarm is declared if more than a critical number of precursors are observed in a specified time window. When an alarm is declared, pilot fraction is increased (by X%). This increment is proportional to the number of events counted during the observed time window. This actuation effectively distributes a larger fraction of total fuel to the pilot when LBO proximity is close (more events in a given time). The control algorithm declares an ongoing event when the sensor signal drops below the lower threshold, and it continues until the signal returns to a point above the upper threshold. During this time, small increments (of Y%) are made to the pilot fraction. Thus, during longer events, which indicate closer proximity to LBO, the system will provide a larger increase in pilot fuel fraction. If no alarms occur during a preset time limit (T), the combustor is considered to be in a safe operating condition, and the pilot fraction is decreased (in multiples of Z%). The decrement is proportional to the time elapsed since the last detected alarm. This improves the response time of the controller to changes in operating condition of the combustor. As noted earlier, two threshold levels are used: a lower threshold for event start and an upper threshold for event end. This allows for better noise rejection and can be customized to suit specific combustors. To account for the drift in the signal levels caused by power setting variations and partial soot deposition on the fiber tip, the mean value of the signal, which is used to normalize the thresholds, is updated every second with the average of the sensor signal over the previous second.

Several parameters can be manipulated to achieve an acceptable tradeoff in terms of response time and sensitivity. The threshold values can be tuned to change the precursor event detection sensitivity. Time-based quantities such as signal mean, alarm count, and time limit depend upon the duration of the time window in which these parameters are evaluated. Longer times for calculating the mean can lead to increased possibility of false alarms caused by power setting changes in the engine. Shorter times increase the likelihood that the mean will be affected by the precursors, thus influencing the sensitivity of the event detection method. The threshold values used will also affect the noise rejection capability of the sensor. Because the algorithm uses the absolute numbers for events instead of average number per time window, the length of the time window used to count the number of events will also become a parameter that affects the response of the controller.

Sensitivity of the control actuation is governed by the increments (X and Y), decrement (Z) and the wait time before decrement (T) to the pilot split fraction, which describes the magnitude of the system response. The critical number of events for declaring the alarm will determine how close to LBO limit we can approach with this algorithm, which avoids LBO. The waiting time T and the critical number of alarms add some dead response zone in the controller, which will reject noise and limit sensitivity.

### 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 airflow rate was independently varied. For both cases, the time window was set to 1 s, and the sensor 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 (during the 1-s window).

To test the behavior of the controller at constant conditions, an experiment was conducted at an overall $\phi$ that would result in blowout without any pilot fuel. Therefore, the system was started (before the controller was turned on) with roughly 14% pilot fraction. It can be seen from Fig. 11 that the controller eventually produces a nearly stationary operating condition. The minimum allowable pilot fraction appears to be 14% based on the effective safety margin set by the chosen controller parameters. Because 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%. The decrement in this case was held constant rather than changing with time depending on the time from the last event.

Figure 12 shows the behavior of the closed-loop system when there are fluctuations in the operating conditions. In this case, the decrements were not held constant, and the starting conditions were

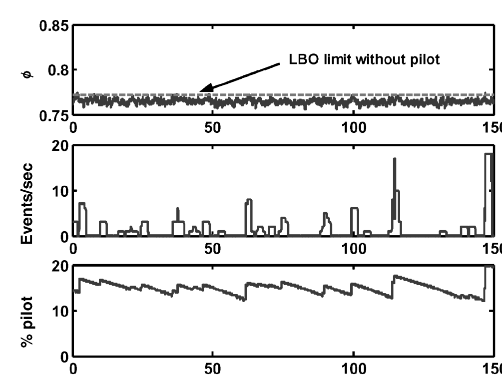


**Fig. 11 Response of the integrated control system to nominally stationary operating conditions.**

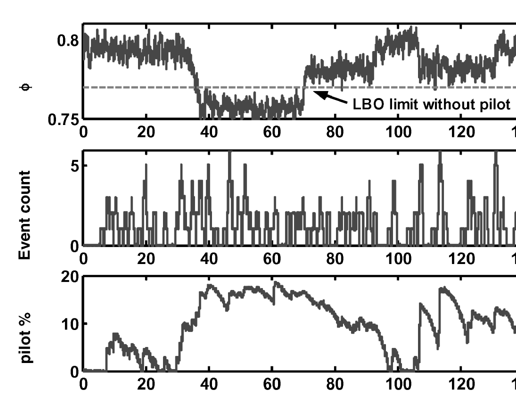


**Fig. 12 Response of the integrated control system to varying operating conditions.**

chosen such that the combustor was stable without piloting. The airflow was manually varied, with the overall $\phi$ changed at a maximum rate of 0.03 $s^{-1}$. The controller successfully used the number of alarms to maintain safe operation of the combustor. During periods when the overall combustor operating conditions were above the unpiloted LBO limit, the control system operated with low pilot fractions. When $\phi$ was decreased below the unpiloted LBO limit, the controller increased the pilot fraction to about 15–18%. When $\phi$ was held constant below the unpiloted LBO limit ($35 < t < 70$ s), the combustor was stabilized by the controller, and the pilot fraction was also roughly maintained at a constant value. For $70 < t < 95$ s, the combustor operated essentially at the unpiloted LBO limit, and the control system found a new stationary point (pilot fraction ~10%). When the air was finally decreased to a point where $\phi$ was well above the LBO limit, the controller eventually diverted all of the fuel back to the main flow.

The oscillatory behavior of the controller at $t > 105$ s is caused by nonoptimized decrement and increment rates. When the combustor has been safe for some time, the decrement rate increases, and the high rate of change of stability will trigger a set of precursor events, which in turn triggers a high increment of pilot fraction. This is caused by the random nature of the occurrence of the precursor events. This can be one of the drawbacks of this algorithm whose decrement steps increases when it is safe. Clearly, the control algorithm can be further optimized to suit a specific combustor and application.

## Conclusions

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

The approach of LBO is detected by monitoring OH chemiluminescence with an optical fiber and a remotely located, compact 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 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 $\phi$ in the flame stabilization zones. Among various piloting approaches investigated, a central preinjection pilot was found to work best. This pilot decreased the LBO limit (based on overall $\phi$) for pilot fractions as low as 5%. The LBO precursor sensing successfully tracked the increase in LBO margin with increasing pilot fraction. The $NO_x$ index of the combustor emissions increases with increased pilot fraction. When compared with the $NO_x$ emissions from the unpiloted combustor at the same safety margin, however, the $NO_x$ index decreased (23% at 0.04 margin). Thus the piloting approach can decrease $NO_x$ emissions without compromising stability and performance.

An effective system controller was developed for closed-loop control of an atmospheric pressure swirl-dump combustor, with ~100-MW/$m^3$ power density. This controller did not require the predetermination of the safe operating regimes of the combustor. 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 $NO_x$ 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 $NO_x$ 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 $NO_x$.

Because 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 improvements to the control scheme could be towards optimizing the tuning variables in the algorithm for specific combustor applications or towards removing the instability in the control scheme caused by random occurrence of the precursor events.

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