SUMMARY REPORT OF:

REAL-TIME CONTROL OF LEAN BLOWOUT IN A TURBINE ENGINE FOR MINIMIZING NO_X EMISSIONS

NAG 2-1488

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I. EXECUTIVE SUMMARY

This report describes research on the development and demonstration of a *controlled combustor* operates with *minimal NO_x emissions*, thus meeting one of NASA's UEET program goals. NO_x emissions have been successfully minimized by operating a premixed, lean burning combustor (modeling a lean prevaporized, premixed LPP combustor) *safely* near its lean blowout (LBO) limit over a range of operating conditions. This was accomplished by integrating the combustor with an LBO precursor sensor and closed-loop, rule-based control system that allowed the combustor to operate far closer to the point of LBO than an uncontrolled combustor would be allowed to in a current engine. Since leaner operation generally leads to lower NO_x emissions, engine NO_x was reduced without loss of safety.

II. Motivation and Objectives

Through the Ultra-Efficient Engine Technology (**UEET**) program, NASA and aircraft propulsion system manufacturers have expressed great interest in research and development of revolutionary technologies that will: (1) provide *"dramatic increases in efficiency to enable reductions in CO_2;"* and (2) allow *"70% NO_x emissions reduction at takeoff and landing conditions"* and also *"enable aircraft to not impact the ozone layer during cruise operation."* While the former goal can be addressed primarily through improvements in compressor and turbine performance, significant reductions in NO_x will require advances in combustor technology. The required reductions in NO_x are even more challenging, considering that future engines are likely to have higher pressure ratios and temperatures, in order to achieve the desired improvements in engine efficiency and, therefore, CO_2 emissions.

II.A Low Emissions Combustors

A number of approaches have been investigated for lowering NO_x emissions. For example, lean burning combustors offer great promise for reducing NO_x emissions. In so-called LPP combustors (*L*ean *P*revaporized *P*remixed), the fuel is quickly atomized, mixed with heated air and vaporized before entering the combustion zone in order to achieve lean premixed combustion. This mode of burning has significant advantages over its nonpremixed counterpart in achieving low pollutant emissions, particularly in regards to NO_x and soot.[1]

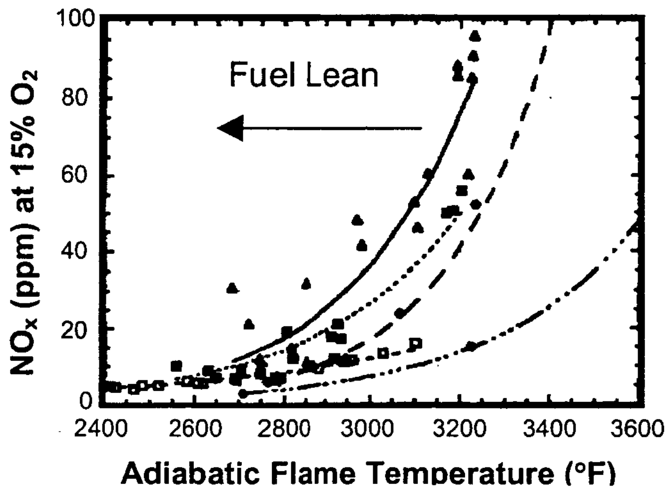


Figure 1. NO_x emission results for various aero-engine, lean-burning (prevaporized fuel) combustors.[2] Generally, lower adiabatic flame temperatures are achieved by using a more fuel lean mixture.

For example, Fig. 1 shows NO_x emissions from premixed combustors operating with various fuel-air ratios. As the equivalence ratio is lowered (leaner operation), the adiabatic flame temperature drops and the NO_x emissions are reduced. For partially premixed combustors, which have at least some regions of the combustor that achieve peak temperatures close to the stoichiometric/maximum value, NO_x emission levels are typically controlled by the thermal (Zeldovich) mechanism.[3] On the other hand, a well-designed LPP combustor can produce ultralow NO_x levels, with the lower limit dependent on the prompt (Fenimore) or N_2O mechanisms, rather than the higher temperature Zeldovich mechanism.[3] However, LPP combustors are also prone to transient flame holding issues, such as inability to stabilize the flame in the combustor[4] and flashback into the prevaporizer section.

II.B Lean Blowout

A significant issue for both LPP-type combustors and conventional (partially premixed) combustors is flame stability during lean operation, i.e., lean blowout, which can result in a severe operability loss. Flame stabilization involves competition between the rates of the chemical reactions and the rates of turbulent advection and diffusion of species and energy to and from the flame, and includes local ignition and extinction behavior. As the equivalence (or fuel-air) ratio of a reaction zone is reduced, extinction events become more likely, and the lean limit for stable operation may be reached. For example, Fig. 2 shows a nominal stability curve for a premixed combustor. The combustor loading parameter is a function of the reactant flow rate and combustor size. In a conventional combustor, LBO can typically occur when the fuel flowrate is reduced too rapidly compared to the compressor response time. If the compressor spools down too slowly, the air flow remains high while the fuel is reduced, leading to lean operation. Thus LBO in a conventional combustor can also limit engine deceleration rate.

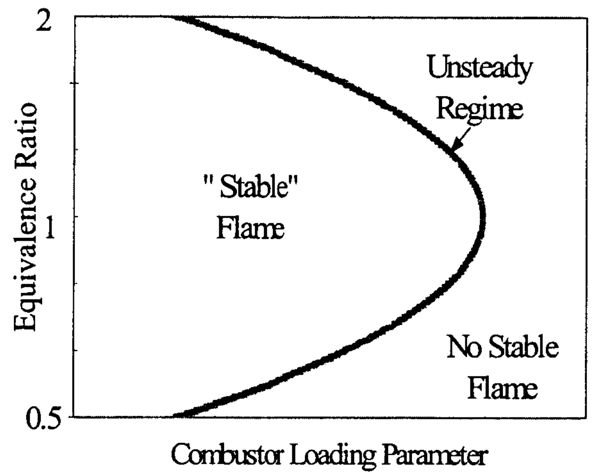


Figure 2. Characteristic stability map for a premixed combustor showing regions where sustainable combustion is possible, i.e., to the left of the stability limit curve.

For an engine designer, the challenge is to develop a combustor that achieves stable operation and low NO_x emissions over the full range of engine conditions. Thus, the combustor designer must build enough margin into the design to prevent LBO at the worst case operating condition. Consequently, there can be an increase in NO_x production compared to what could be optimally achieved at other operating conditions. Furthermore, when coupled with overall engine system dynamics, flame blowout can result in the inability of an engine to recover from a compressor stall event.[5]

III. Summary of Accomplishments

Under this program, an atmospheric pressure, swirl-stabilized combustor (Fig. 3) was fabricated. It was designed to be a simplified model of a lean, premixed gas turbine combustor that includes a swirl inlet. In this design, a combustible mixture of fuel (methane or natural gas) and air flow passes through swirl vanes housed in a 22 mm i.d. tube, producing a swirl number of ~0.4. Upon leaving the swirler, the flow expands into a cylindrical, quartz combustor of 70 mm i.d.. The combustor typically operates with an average (post-combustion) gas velocity of 6-9 m/s. At these conditions, the LBO limited equivalence ratio is approximately 0.73-0.76 (see Fig. 4), depending on the combustor wall temperature. We have successfully demonstrated early detection of precursor events to lean blowout using both acoustic and optical approaches, and closed-loop control to minimize NO_x emissions, while simultaneously operating near the LBO limit without blowout.

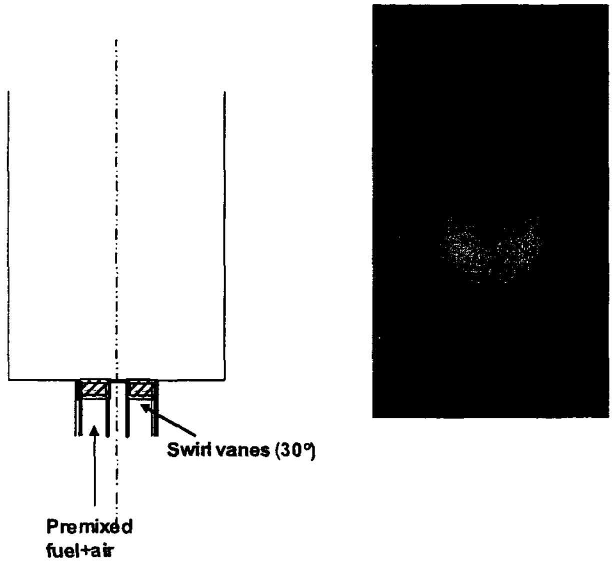


Figure 3. Schematic (left) of the swirl stabilized dump combustor and photograph (right) of the combustor operating at equivalence ratio of 0.75.

III.A LBO Sensing

The sensing strategy for LBO precursors is based on the notion that flame blowout is preceded by a transient period. This period is marked by localized extinction and reignition events, and therefore irregular rates of fuel consuming reactions and the associated heat release. In addition, this leads to large-scale flame unsteadiness. These events can be detected either by: 1) **acoustic sensors**, which respond to the acoustic waves produced by the unsteady heat release, via **unsteady volumetric expansion**; or 2) **optical sensors** that respond to the unsteady reaction rate of elementary steps in the oxidation of the fuel that produce electronically excited molecules that can then fluoresce, i.e., produce **chemiluminescence**. For example, Fig. 5 shows signals from both acoustic and optical sensors (acquired simultaneously) at an equivalence ratio close to the LBO limit. The instances associated with the local extinction/reignition events are marked by large excursions in the signal for both sensors, with the optical sensor showing the greater sensitivity.

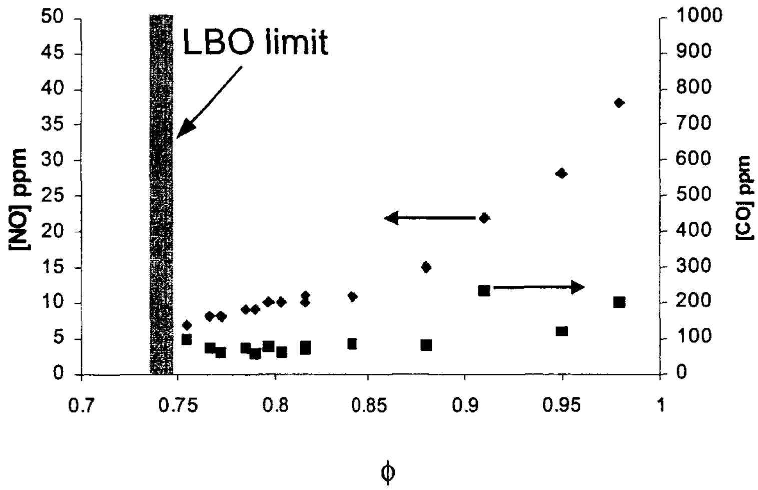


Figure 4. Emissions and LBO limit of the swirl stabilized, premixed combustor.

We have explored various options (spectral, statistical, and event-monitoring methods) for analyzing these signals to sensitively and reliably detect a quantity that indicates "nearness" to LBO. For example, Fig. 6 shows the results of a narrow-bandwidth spectral approach looking at low frequencies (and is therefore a measure of large scale flame unsteadiness). The amount of unsteadiness of the signal in a low frequency range (51-53 Hz) can be seen to increase rapidly as the combustor approaches its LBO limit. Another technique that works especially well with the optical sensor is based on simply counting the number of times that the chemiluminescence falls below some threshold level (see Fig. 7). This simple approach requires less computational resources than the spectral method, and can be easily applied to rapid detection requirements (e.g., by looking for single events).

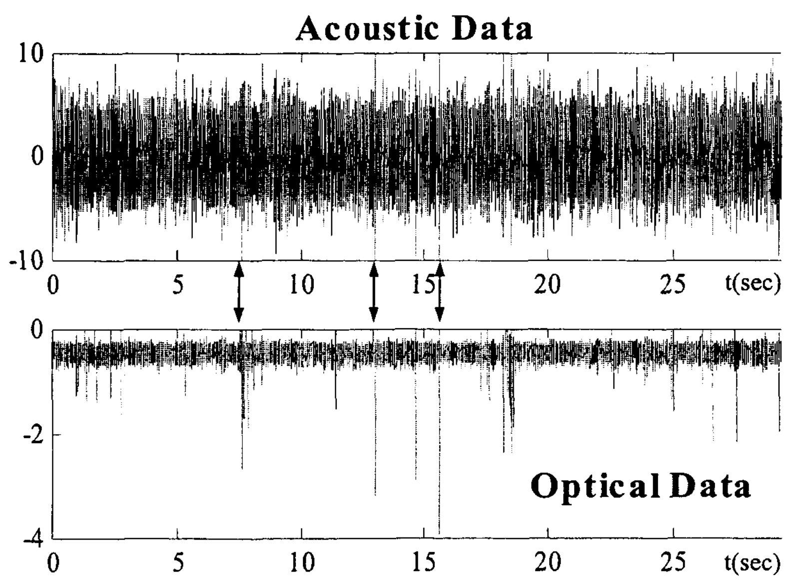
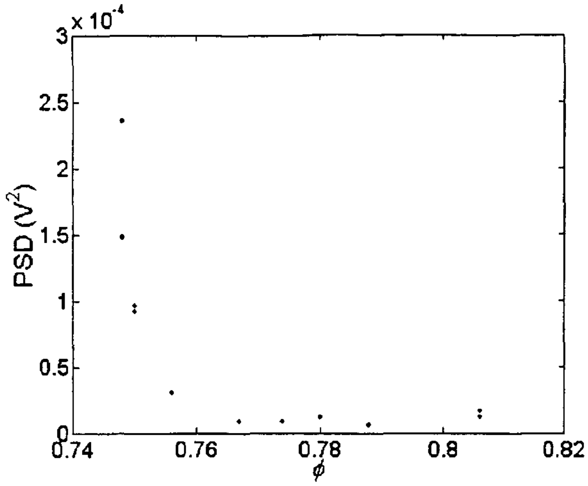


Figure 5. Simultaneous data traces from the acoustic (microphone) and optical (photomultiplier tube – a more negative output corresponds to increasing optical signal) sensors at an equivalence ratio near the LBO limit. For illustration, three of the sudden heat release events are indicated by arrows.



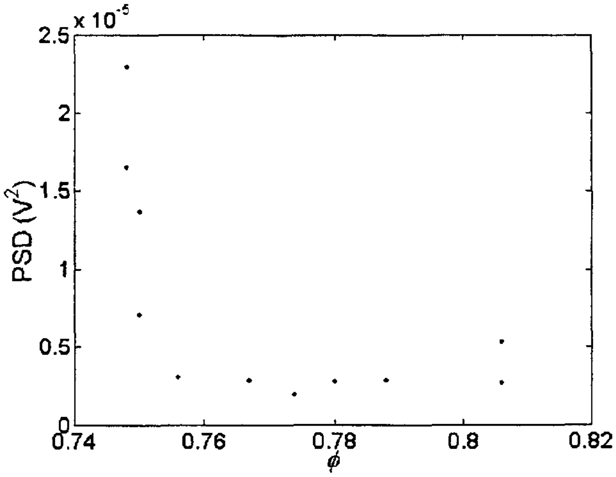


Figure 6. Power spectral density integrated within a 51-53 Hz range for acoustic (left) and optical (right) sensors as a function of combustor equivalence ratio.

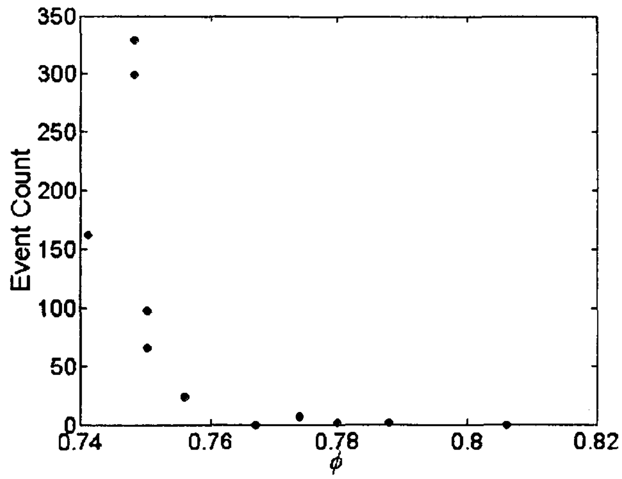


Figure 7. The number of large deviations in the optical (chemiluminescence) signal over a fixed time period (10-20 seconds) as a function of combustor equivalence ratio.

III.B LBO Control Actuation

While there are various possible actions a control system could take to avoid LBO without changing the engine power setting, the current work focused on the redistribution of the fuel inside of the combustor. This approach has the advantages of 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.

III.B.1 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 8 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 9) show that the pilot fluid mixing is extremely rapid, supports the mixing argument.

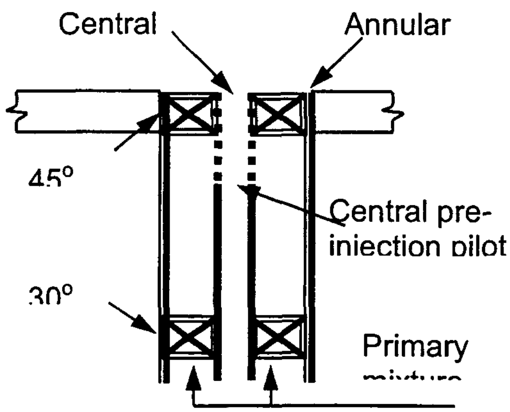


Figure 8. Schematic showing the various pilot options discussed. The central pre-injection pilot is the case used in the control experiments.

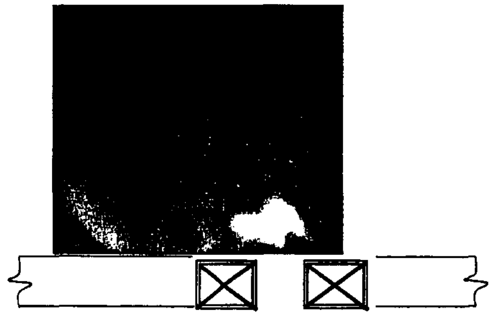


Figure 9. Schlieren image of the central pilot injected into cold flow. The jet does not penetrate more than one diameter into the combustor. Bright region at the left bottom corner of the image is an artifact of aberrations in the glass.

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.

III.B.2 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 10 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.

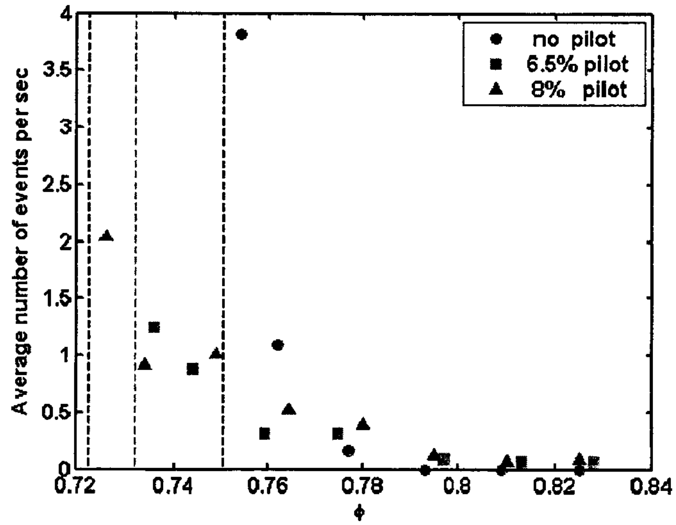


Figure 10. Average number of events per sec as a function of equivalence ratio for various pilot fractions, with nominally same velocity field. The dotted lines indicate the respective LBO limits for each case.

III.B.3 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 11, 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.

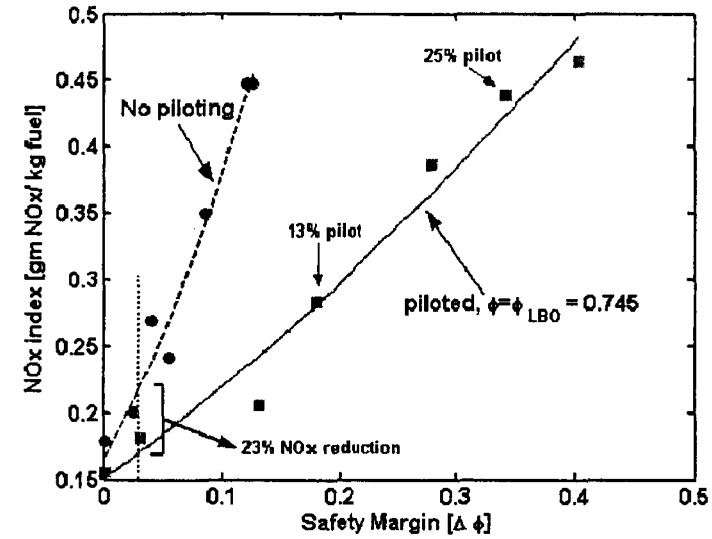


Figure 11. NOx as a function of safety margin for piloted and unpiloted operation of the combustor.

III.C NO_x and 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.

III.C.1 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.

III.C.2 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 12. 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.

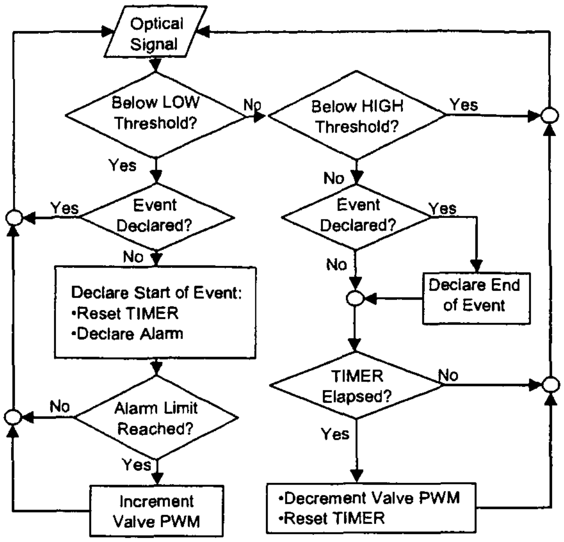


Figure 12. Algorithm followed by the controller.

III.C.3 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.

III.C.4 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 15** 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%.

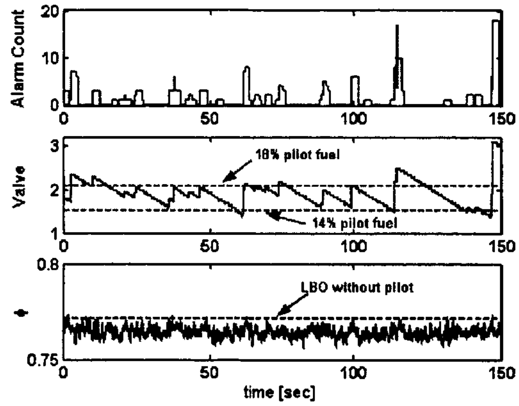


Figure 13. Response of the integrated control system to nominally stationary operating conditions.

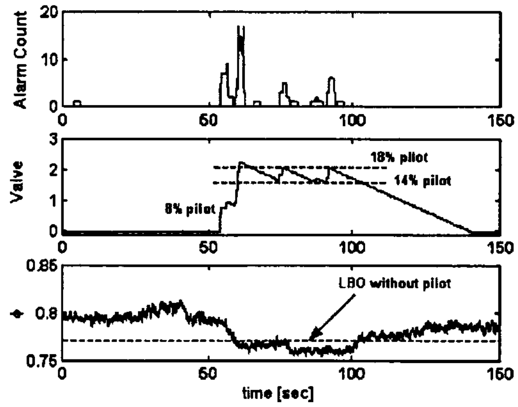


Figure 14. Response of the integrated control system to varying operating conditions.

Figure 14 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 $t \cong 54$s). 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.

We have also developed a flexible controller architecture that works to minimize a cost function (made up of an arbitrary set of combustor "outputs", e.g., NO_x, CO, and noise emissions), while simultaneously protecting against LBO. The controller is based on a simple rule-based approach that examines the trend in the cost function versus the control action. Actions that decrease the cost function are continued until the cost function rises, or until alarms are raised by the LBO sensors. An example of the system response is shown in Fig. 15, where the system lowers the overall fuel flowrate in order to optimize the NOx levels.

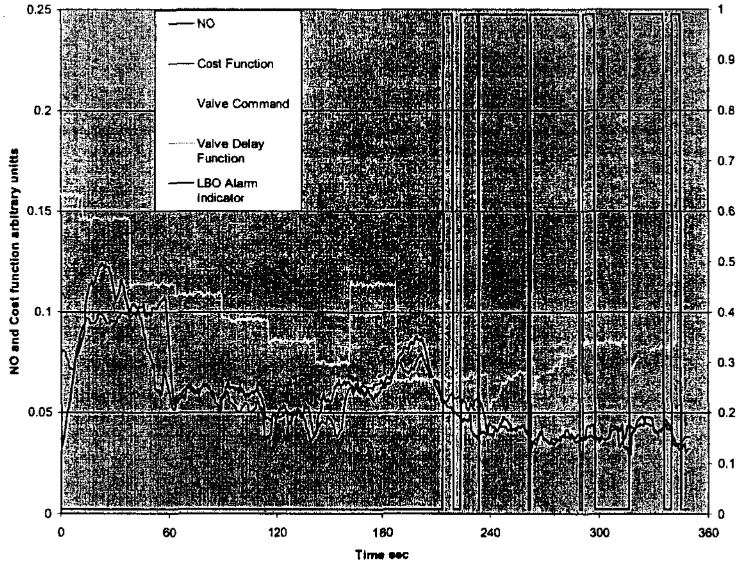


Figure 15. Response of the integrated control system as a function of time, showing how NOx is reduced (and minimized) until a point is reached where the LBO sensor alarms are too frequent.

IV. References

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