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Chemiluminescence Based Sensors for Turbine Engines

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ABSTRACT

This work focuses on the use of naturally occurring optical emissions, specifically chemiluminescence, for sensing applications in active control and health monitoring of combustors. First, monitoring local equivalence ratio (ϕ), at the reaction zone, has been demonstrated using the ratio of CH to OH chemiluminescence. This ratio (CH*/OH*) increases monotonically with equivalence ratio, and the dependence on equivalence ratio has been shown to be a universal function for combustor configurations ranging from unconfined jet flames to swirl and dump stabilized combustors. There is essentially no difference between the CH*/OH* ratio for methane and natural (city) gas, but the ratio has a lower sensitivity to ϕ for n-heptane compared to methane or natural gas. The ratio was found to increase almost linearly with pressure for natural gas/methane combustion above 3 atm. Second, chemiluminescence emission from the combustor was used to detect precursor events to blowout, using a robust thresholding method. This method was shown to be successful in jet flames and swirl/dump stabilized combustors using premixed methane/air and nonpremixed Jet-A/air. This method gives the kind of information on proximity to blowout that can be used by an active control system to prevent lean blowout in low NO_x turbine engine combustors.

INTRODUCTION

Both active control and health/performance monitoring systems for turbine engine combustors require knowledge of the state of the combustion processes within the combustor. For example, active control can be an efficient way to expand turbine engine combustor operating limits without loss of performance and safety. In the area of emissions control, it is known that NO_x can be reduced by use of low fuel-air ratios in the flame region. However, operation under these conditions also makes the combustor prone to lean blowout (LBO) problems. Thus sensors that could give advance warning of LBO, in conjunction with an active control system, would

permit lower emissions operation. In a similar way, significant variations in local equivalence ratio in premixed or partially premixed combustors can lead to temperature nonuniformities that will increase NO_x emissions and decrease the useful life of the turbine. Thus active control or engine health monitoring systems would be aided by sensors that could monitor fluctuations in local flame zone equivalence ratio inside a combustion chamber.

In general, reliable and versatile sensors are required. For most engine applications, they must also provide measurements of conditions at locations away from the combustor wall, thus nonintrusive methods are preferred. In addition for active control systems that use state feedback, the sensor time response is also an important issue. Optical sensors offer the benefit of being able to gather data from extremely hostile environments (e.g., the combustion zone), and to do so over large regions of space. With the rapidly growing capability of these technologies for sensor hardware, there is an increased interest and need to develop data interpretation strategies that will allow optical flame emission data to be converted to meaningful combustor state information, such as heat release rate, proximity to LBO, and local flame zone equivalence ratio.

There are a number of optical methods that can give information about the combustion process non-intrusively, e.g., optical emission, absorption, fluorescence and other spectroscopic methods. The focus of this work is on the simplest of all these techniques, viz., observing the naturally occurring, optical emissions from the combustor. While there are a number of sources for optical radiation from a combustor, the source most directly connected to the combustion reactions is chemiluminescence. This radiation is from high energy states of molecules (typically electronically excited states) that are produced by chemical reactions. Once produced, the excited molecules will transfer to lower energy states, in part by emitting light. This is known as chemiluminescence. Since the intensity of emission is proportional, in part, to the chemical production rate of the particular molecule, the chemiluminescence intensity can be related to (specific) chemical reaction rates.¹ For this reason, chemiluminescence has been used previously as a rough measure of reaction rate and heat release rate.²⁻⁸ Thus chemiluminescence can

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provide information on the presence and strength of the combustion process in a specific region of the combustor, making it well-suited for health monitoring and diagnostics.

Since the chemiluminescence intensities relate to the species that are produced during the reaction process, the intensity of light produced is related to the rate of production/depletion of that species. These rates vary with reaction pathways which is a function of equivalence ratios, making it easier to deduce the equivalence ratio from the chemiluminescence intensities. It has been shown that the ratios of chemiluminescence from different molecules, e.g., OH*/CH* and C₂*/OH*, vary with equivalence ratio in simple flames.⁹⁻¹³ Morrell *et al.*¹⁴ used the C₂*/OH* ratio to determine the axial evolution of the local equivalence ratio in a nonpremixed, liquid-fueled combustor at atmospheric conditions.

Practical combustors usually operate at a range of pressures usually higher than atmospheric pressure. Since pressure can change the reaction mechanisms, the number density of the radicals and thus the chemiluminescence signal will be affected by change in pressure. Higgins *et al.*¹¹ and Ikeda *et al.*¹² have investigated the behavior of OH and CH chemiluminescence at high pressure in simple, laminar methane-air flames. There is little data in the literature for more complicated combustors (e.g., turbulent or swirl stabilized), especially at elevated pressures. This work demonstrates the usefulness of chemiluminescence as a useful diagnostic tool for combustion processes in a variety of combustors, over a range of pressures, and for a number of fuels.

As noted above, sensing of proximity to the blowout limit in combustors is also an important issue for combustor health monitoring. Lean blowout in combustors has gained attention among researchers due to the increasing constraints on NO_x emissions constraints in the turbine engine industry. Flame stability has been studied close to blowout by a number of researchers.¹⁵⁻²³ The focus was mainly on understanding the mechanisms that influence the loss of stability. This is usually attributed to high heat loss and strain rates.

A handful of researchers have focused on detecting the approach of stability loss. Some observed significant flame instability near lean blowout and noted that there was a considerable amount of time when there was essentially no flame present in the combustor.^{15,24-30} Muruganandam *et al.*³¹ showed that the approach of LBO can be detected by observing the OH chemiluminescence from specific locations in a gas-fueled, atmospheric pressure, non-preheated, swirl-stabilized combustor. Since this work focuses on the usefulness of chemiluminescence emissions from the combustor, the precursor events to blowout of the

combustor were also used to give information about the proximity of the blowout limit from the operation conditions. Various combustors have been used to show the robustness and applicability of the techniques.

EXPERIMENT SETUP

CHEMILUMINESCENCE COLLECTION

Chemiluminescence is collected using two systems. The first models a practical sensor device and employs a 365 μm fused silica optical fiber. The fiber has a numerical aperture of 0.22 which allows it to collect light from a conical region of half angle of 12.5°. The collected light passes through appropriate interference filters (308 nm center wavelength for OH* and 430 nm for CH*, both 10 nm full-width-half-maximum) and is detected by miniature, metal-can photomultiplier tubes (PMT, Hamamatsu H5784). The location of the fiber determines the region of the flame observed (this gives the flexibility of choosing the viewing volume). For most of the measurements, the fiber was used only to demonstrate LBO detection and thus the fiber collected light from a region very close to the stabilization zone or the bright flame zone. Since the PMT has a very fast time response (20 kHz bandwidth) it can be used to monitor temporal variations of chemiluminescence in the combustor.

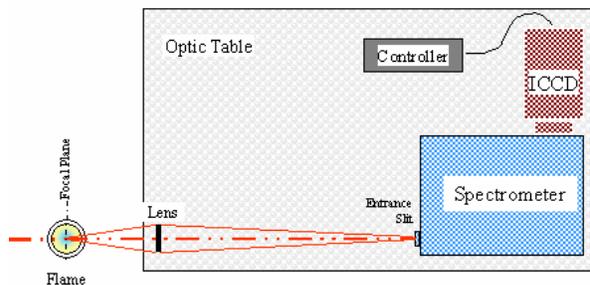


Figure 1. Schematic of the imaging spectrometer setup used to obtain the emission spectra from the combustors.

The second detection system employs an imaging spectrometer (300 groove/mm grating) coupled to a 1024×256 intensified CCD camera to simultaneously capture the ultraviolet and visible optical emission spectrum (~280–550 nm). In order to mimic the anticipated resolution of practical engine optical sensors, the resolution of the spectrometer is typically set to ~5-10 nm through control of the entrance slit width. With this setup, flame spectra can be acquired with relatively low temporal resolution (~10 Hz).

COMBUSTORS

Experiments were conducted in various combustors from simple open flames to combustors that emulate many aspects of practical, turbine engine combustors. Both premixed and non-premixed/partially premixed combustors were used in this study.

PREMIXED COMBUSTORS

Three types of premixed combustors were employed: 1) a ring-pilot stabilized, unconfined jet flame, 2) an atmospheric pressure, swirl stabilized, dump combustor with circular cross-section and 3) a high pressure, gas turbine combustor simulator, with square cross-section.

The ring-pilot stabilized, jet flame used both methane and natural gas as fuels. The jet inner diameter was 0.91" with a step on the outside of the lip of the burner, where the pilot mixture (usually slightly fuel rich) was injected through 25 holes. The pilot flow rates were very small compared to the main flow rates. The main jet exit velocity was ~5m/s, with a Reynolds number based on jet diameter of ~5000. The spectrometer collected the optical emission from a 1×15 mm region centered on the axis of the flame, far enough downstream where the effect of the pilot flame was negligible.

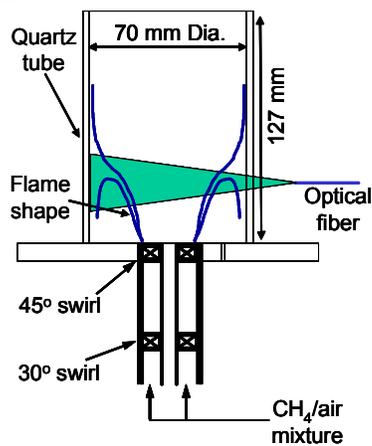


Figure 2. Schematic of the Swirl stabilized dump combustor used in this work. The location of the fiber, its collection volume and flame shape are also shown.

A schematic of the second combustor used is shown in Figure 2. The overall combustor configuration was chosen as a simplified model of a lean, premixed, gas turbine combustor that includes a swirling inlet section. 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 0.66.³² The quartz wall permits uncooled operation of the combustor and facilitates detection of ultraviolet (UV) radiation. 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. Also shown in figure are the nominal flame shape and the location of the optical fiber used to collect optical emissions.

The third premixed combustor (Figure 3) is a high pressure, gas turbine combustor simulator.³³ The facility consists of modular inlet, combustor and exhaust sections. High-pressure air and natural gas are supplied through building lines capable of providing 720 and 1000 psi pressures, respectively. Both the air and fuel flow rates are measured through the use of calibrated critical orifices. The equivalence ratio was kept constant by double choking of both air and fuel flow paths. The fuel-air mixture enters the circular 4.75cm diameter, 60cm long inlet section and passes through a 45° swirler prior to entering the combustor. Combustion occurs in the 51 cm long, 5×5cm square combustor downstream of the conical flame holder, and the combustion products then flow through a circular 7.6cm diameter, 195cm long exhaust section before leaving the system. A separate high-pressure air stream cools the combustor walls, and is then injected through a tube into the exhaust section where it mixes with the combustion products. Tests were performed at pressures ranging 1.5 to 10 atm, over equivalence ratios ranging from lean blow out to near stoichiometric with mass flowrates of 10-50 g/sec.

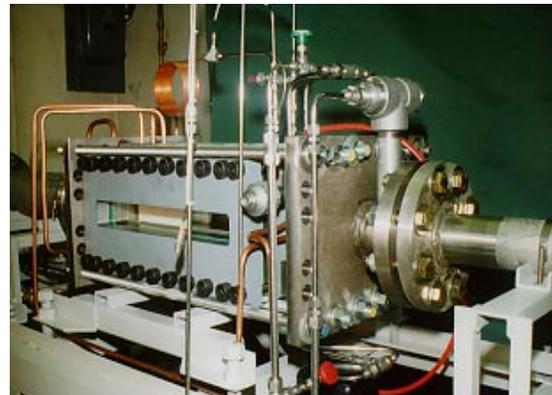


Figure 3. Picture of the high pressure gas turbine combustor simulator.

NON-PREMIXED COMBUSTORS

Two non-premixed, liquid fueled, atmospheric pressure, swirling combustors were used in this study: 1) an axisymmetric, air-staged combustor, and 2) a single cup, annular section model of a CFM56 combustor.

The first non-premixed combustor³⁴ used n-heptane (C₇H₁₆) fuel, which is supplied to the bottom of the combustor through a modified pressure-atomizer. One-third of the air premixes with the fuel spray in a central diverging tube, and the remaining air mixes with the central flow downstream of the diverging tube. The combustor walls are made of 42 mm diameter quartz tube. The maximum airflow rate is ~15 g/s and the maximum fuel flow rate is ~1 g/s. The lean stability limit of the flame without air preheating is at an overall equivalence ratio of ~0.6.

The CFM56 single cup combustor uses a burner head with co-annular, counter rotating swirlers. The standard fuel nozzle was replaced with a pressure-swirl atomizer. The combustor air comes from an air plenum chamber fed by electrically heated air (~400 K). The test-section is optically accessible through quartz side walls. The combustion gases exit through a small converging nozzle to provide a more realistic boundary condition. The fuel used for these experiments was Jet-A aviation grade petroleum.

RESULTS

CHEMILUMINESCENCE SPECTRA

Figure 4 shows the spectral distribution of chemiluminescence emission from the atmospheric pressure, jet flame at 0.85 equivalence ratio. It can be seen that OH and CH are the primary narrowband emitters for lean natural gas combustion (for rich combustion, C_2 chemiluminescence is also important). However, there is also a significant background of broadband emission due to chemiluminescence from other sources, such as HCO^* and CO_2^* .^{6,12} This background is especially significant when the spectral bandwidth of the detection system is 5-10 nm or greater, as might be expected for a practical engine sensor (and for the detection systems employed here).

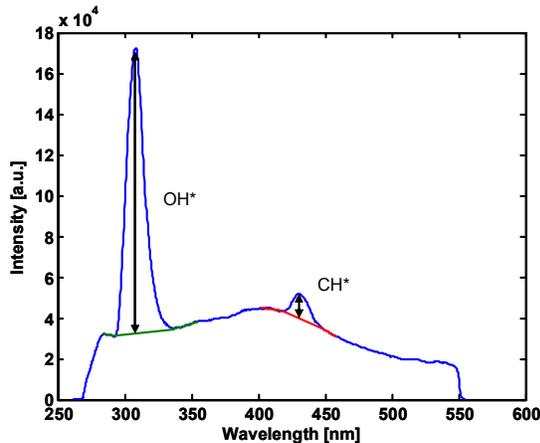


Figure 4. Typical chemiluminescence emission spectrum from the pilot stabilized, atmospheric pressure, jet flame. Also shown here is the quadratic fit for background correction used to subtract out the broadband emission.

EQUIVALENCE RATIO SENSING

Thus to get a more accurate measure of chemiluminescence intensities from OH^* and CH^* alone, background correction based on the side bands can be used.¹⁴ Figure 4 shows the polynomial fit based on the side bands, used to correct for background emissions from other species. It is essentially a quadratic fit to the spectrum around the primary peak. The curve fit value at ~308 nm is subtracted from the intensity measured, to get a corrected OH^* peak intensity, and likewise at ~430 nm for CH^* .

As noted above, the CH^*/OH^* ratio is known to vary with equivalence ratio, but most of the previous efforts studied simple flames. The main focus of this work was to study the effect of combustor configurations, fuel variations and pressure changes on this ratio, with motivation towards using the observation to get useful information about the combustion process itself.

EFFECT OF COMBUSTOR

Figure 5 shows the variation of the CH^*/OH^* ratio for averaged chemiluminescence signals acquired with the spectrometer system from two different methane-air premixed combustors. One is the unconfined jet flame, the second is the swirl/dump stabilized combustor. The data from the jet flame have been multiplied by a constant to account for a change in the entrance slit width used in the two cases. It can be seen that the general trend in the CH^*/OH^* ratio with equivalence ratio remains the same, irrespective of the combustor geometry. The main differences between these two combustors are the swirl and complex flow structure (significant recirculation and three-dimensionality) in the swirl/dump stabilized combustor. These flow features should cause local variations in strain and temperature in the combustion zone. (Note, the uncooled quartz walls in the swirl combustor prevent significant heat losses in that combustor). Thus, the lack of dependence on flow geometry indicated by the results of Figure 5 indicates that turbulence induced strain does not significantly alter the CH^*/OH^* trend with local fuel/air ratio. This result supports the work by Higgins *et al.*,¹⁰⁻¹¹ who observed only weak strain effect on CH and OH chemiluminescence in opposed flow, laminar flames.

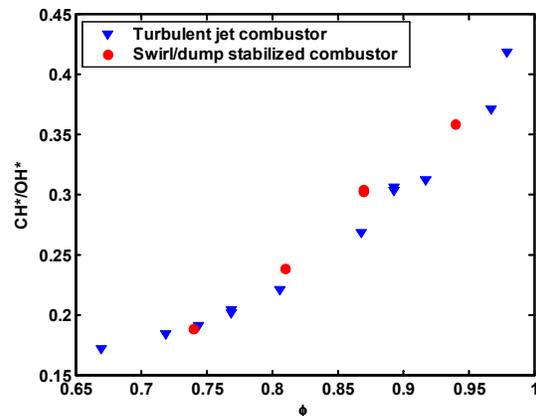


Figure 5. Comparison of CH^*/OH^* for premixed methane air combustion in a turbulent jet flame and in a swirling dump combustor.

Since the dependence of the ratio on ϕ appears to be universal across combustor configurations and flowfields, a sensor developed based on this method should have wide applicability. Of course, such sensors would either have to be calibrated to account for

variations in spectral response* or the ratio must be measured at least at one operating condition where equivalence ratio is known.

EFFECT OF FUEL

The variation of CH^*/OH^* with fuel (as well as combustor geometry) is shown in Figure 6. Natural gas and methane give almost the same trend with equivalence ratio for the various combustors. Thus small changes in fuel composition for natural gas fired combustor are unlikely to significantly change the CH^*/OH^* dependence on equivalence ratio. Data from the n-heptane fueled combustor, which were acquired using a monochromator system (with a different spectral response curve),¹⁴ have been multiplied by an arbitrary factor to compare the results. The chemiluminescence ratio for n-heptane also increases with equivalence ratio, but shows less sensitivity than natural gas and methane. This is not surprising, since the fuel-oxidation chemistry for higher order hydrocarbons includes different chemical reaction paths. In fact, Morrell *et al.*¹⁴ showed the C_2^*/OH^* ratio is more attractive for complex hydrocarbons. These fuels produce much more C_2 emission, especially in lean flames compared to methane and natural gas, and that the C_2^*/OH^* chemiluminescence ratio is more sensitive to equivalence ratio changes than CH^*/OH^* .

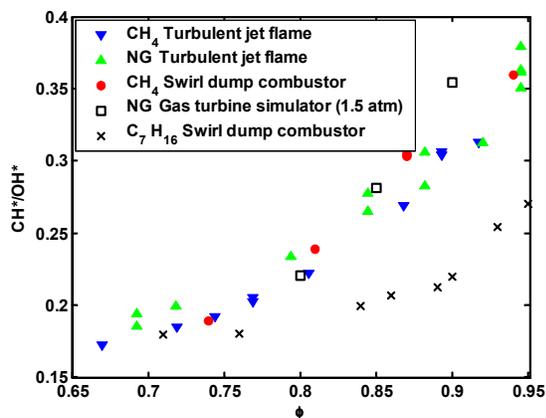


Figure 6. Comparison of the CH^*/OH^* chemiluminescence ratio in the various combustors studied. The gas turbine simulator data is for 1.5 atm, all the other data are at 1 atm pressure. Data from the n-heptane combustor have been multiplied by a constant to compare the trend with ϕ .

EFFECT OF PRESSURE

Most of the data shown above were obtained at atmospheric conditions. While the gas turbine simulator values, acquired at 1.5 atm and shown in Figure 6 are nearly the same as the atmospheric pressure results, there is some difference at high ϕ .

*The current results do not include corrections for the spectral response of the spectrometer/ICCD system.

Thus experiments were conducted in the gas turbine combustor simulator at various pressures (~2-8 atm). As already shown, combustor geometry does not seem to significantly influence the CH^*/OH^* response, so it is expected that the pressure results from this single combustor should be representative of gas turbine combustors. As found for the atmospheric pressure cases, the CH^*/OH^* increases for higher ϕ , with pressure held constant (see Figure 7).

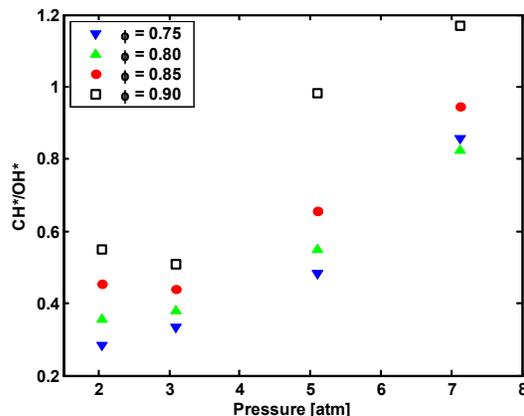


Figure 7. CH^*/OH^* chemiluminescence ratio measured in the high pressure, gas turbine combustor simulator at various pressures (absolute) for fixed mass flow rate (30g/s).

For most conditions, an increase in pressure generally causes a corresponding increase in the CH^*/OH^* chemiluminescence ratio. For the leaner mixtures ($\phi \leq 0.8$), this is always the case, i.e., CH^*/OH^* increases monotonically with pressure (at least for range studied here). For richer mixtures, however, the pressure dependence appears more complicated. There appears to be a pressure region, somewhere below 3 atm, where the CH^*/OH^* actually decreases with increase in pressure. Thus, use of this approach to monitor equivalence ratio (or fuel-air mixing variations) will also require measurement of the combustor pressure. This requirement is not severe, however, since combustor pressures are normally monitored, and because the sensitivity to pressure is not dramatic.

Since the pressure dependence is complex, the higher pressure ($P > 3$ atm) data were used to obtain a least squares correlation fit for the pressure dependence. Since the pressure dependence seen in Figure 7 appears to be nearly linear, a simple power law function was used, and the result was $(CH^*/OH^*) \propto P^{0.94}$. Higgins *et al.*¹¹ also measured the pressure dependence over the range 5-25 atm in a laminar burner, and suggested a correlation of $(CH^*/OH^*) \propto \phi^{-2.51} P^{0.22}$, a much lower pressure dependence than found here. Moreover, the equivalence ratio dependence shown by their

correlation suggests a *decrease* in the CH*/OH* ratio with increased equivalence ratio. This is contrary to the observations in this work and elsewhere.^{9,14}

One possible cause of the difference is heat losses. Higgins *et al.* used a quasi-flat flame burner, in which the flame sits very close to the burner surface. This can cause heat (and radical) losses to the wall. In the current work, a large portion of the flame sits away from the combustor walls. Another likely cause is the presence of the broadband background. Figure 8 shows spectra obtained from the high pressure, gas turbine combustor simulator at an equivalence ratio of 0.8 at two pressures. With a pressure increase, the overall optical intensity of the flame was found to decrease. Although the overall intensity decreases, the OH* and CH* peaks decrease relatively more than the broadband background emission. Thus the CH*/OH* ratio will change depending on whether the background is subtracted. While the data presented here were corrected for the broadband background, the results of Higgins *et al.* are based only on measurements of OH* and CH* using a bandpass filter, which also passes the background chemiluminescence. Thus, their results will also depend on the variation of the background emission in the two spectral regions.

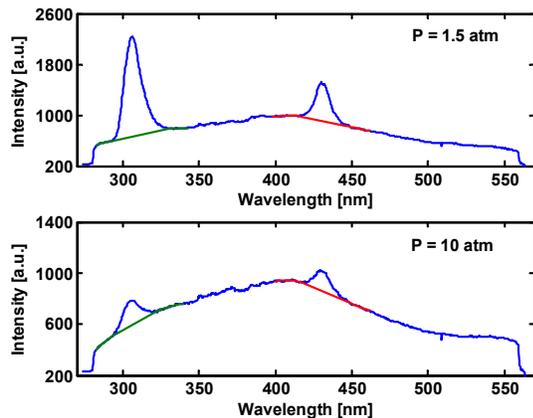


Figure 8. Chemiluminescence spectra from the high pressure, gas turbine combustor simulator at equivalence ratio of 0.8 and at pressures (absolute) 1.5 and 10 atm.

LEAN BLOW OUT SENSING

As noted previously, chemiluminescence has been used as a rough measure of reaction rate and heat release rate. The interest here was to use chemiluminescence to detect sudden changes in the flameholding stability of a combustor, through detection of sudden changes in chemical reaction rates. The approach is to look for short-lived (and often localized) extinction events, which would be followed by a sudden reignition of the fuel/air mixture. As these extinction events occur more often, flame loss, i.e., blowout, becomes more likely.³¹

Figure 9 shows a typical OH chemiluminescence intensity variation from the methane-fueled,

swirl/dump combustor at two operating points, far from LBO, $\phi=0.87$, and close to LBO, $\phi=0.82$ ($\phi_{LBO}=0.81$). The results were obtained using the fiber optic-PMT detection system in order to obtain the necessary time response. There were two fibers looking at the centerline of the combustor from the side, at a height of ~ 62 mm from the dump plane. The two fibers collected the light and delivered to two different PMTs, each with appropriate interference filters (one for CH* and other for OH*) in front of them. The average intensity decreases with equivalence ratio; this is an artifact of the method used to vary ϕ . The leaner mixture was produced by decreasing the fuel flow while keeping the air flow constant, so as to maintain the same nominal velocity field. The mean OH* signal scales roughly with the overall heat release, which in turn scales with the fuel flowrate.

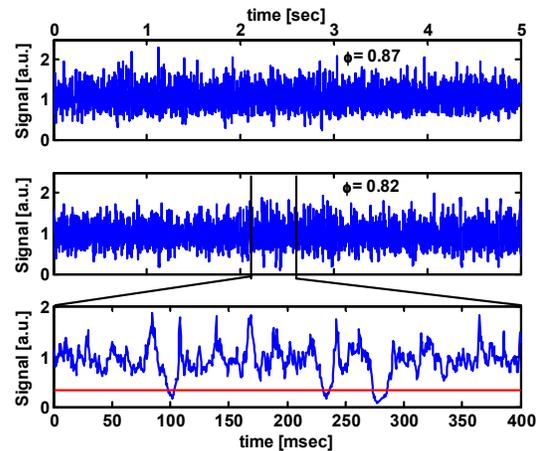


Figure 9. Typical OH* signal from the swirl dump combustor far and close to LBO limit ($\phi=0.81$). Also shown is the thresholding method used to detect the local extinction-re-ignition events from the signal.

More importantly, as the combustor is operated closer to its LBO limit, the OH chemiluminescence more often drops to a “near” zero value, indicating the occurrence of the short duration, extinction events. These events can be identified using a simple, but robust thresholding method, in which the event begins when the signal drops below the threshold level (see bottom graph in Figure 9). The threshold value was taken to be a fraction of the time-localized mean OH* signal rather than a fixed value. This removes the dependence of the overall signal on power setting variations, and long term changes in the fiber (e.g., coating) or detector. Here, the local mean signal at a given time is based on the signal averaged over the previous 0.5 secs.

The CH chemiluminescence signals also show the capability to detect these LBO precursors (see Figure 10). Although the general behavior with time is the same for both OH* and CH*, there are small differences during the events. The OH* extinction

events are usually more distinct compared to the CH* events. Thus the thresholding method might not give the same results for both.

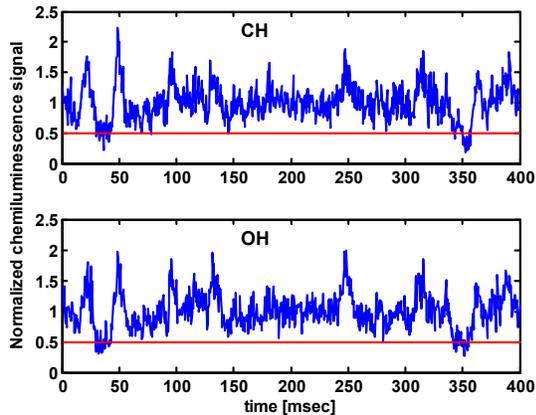


Figure 10. Chemiluminescence signal from the combustor showing both CH and OH signals close to blowout.

The OH chemiluminescence signal was used to detect the precursor events and the average number of events occurring per second is shown in Figure 11 for two different combustors. The thresholds used to detect the events was 30% of the mean signal for the methane/air premixed swirl/dump combustor and 45% of the mean signal for the annular section, nonpremixed, liquid-fueled combustor. The combustors have very different LBO limits (ϕ_{LBO} for the nonpremixed combustor is based on the overall fuel and air flowrates). Thus the data is presented as a function of equivalence-ratio-standoff from LBO, which is the difference in equivalence ratio of operation to that of LBO limit, i.e., $\phi - \phi_{LBO}$. Thus blowout occurs when this parameter is zero. As is evident from the figure, the average number of these events increases as the LBO limit is approached.

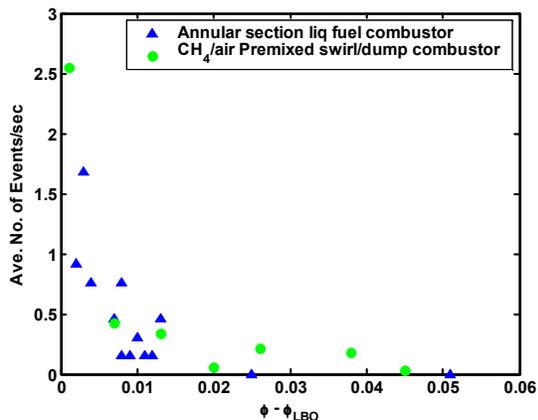


Figure 11. Number of chemiluminescence-based, LBO precursor events/sec in two combustors as a function of proximity to the LBO limit (ϕ_{LBO} = 0.821 for the methane combustor and 0.352 for the liquid-fueled combustor).

These results show that chemiluminescence from a combustor can be effectively used to detect LBO precursors and assess the proximity to LBO. This can be achieved in both premixed and non-premixed combustors, with gaseous or liquid fuel, with or without swirl. Using the suggested thresholding method with normalization by the local mean signal, LBO proximity can be determined whether it is caused by changes in the fuel or air flowrates. In addition, the method should be robust in the presence of long term aging of the combustor and sensor. Although data has been shown for only two of the combustors, this method was found to give similar results in other combustors studied.

SUMMARY

This work has focused on the use of naturally occurring, optical radiation from combustors to give information about the combustion process that would be useful for active control and diagnostics/health monitoring of the combustor. Chemiluminescence emissions from a variety of combustors have been measured. OH* (308nm) and CH* (430 nm) chemiluminescence emissions were studied, since they are the primary narrowband sources in lean, hydrocarbon combustion.

The ratio of peak intensities at select wavelengths has been shown to be a robust measure of local (reaction zone) equivalence ratio in lean burning combustors. This sensing approach would provide a practical way to monitor nonuniformities fuel-air mixing and heat release, which in turn causes nonuniform temperature patterns at the exit of the combustor and can increase NOx emissions.

Peak intensity values were obtained after correction for the broadband background emission. This correction can be important since the background emission may depend differently on the relevant operating conditions (e.g., equivalence ratio and pressure). The ratio of CH* to OH* peak intensities was shown to increase monotonically with increasing equivalence ratio. Natural gas and methane burned in various combustor geometries, from simple, unconfined jet flames to combustors with swirling flows and recirculation zones, gave nearly identical results for the relationship between CH*/OH* and equivalence ratio.

The pressure dependence of CH*/OH* was found to be nearly linear ($P^{0.94}$) at elevated pressures (>3 atm) for these fuels, though there appears to be a more complex behavior for near stoichiometric (and rich?) mixtures at lower pressures. Thus measurement of equivalence ratios in practical devices will require pressure measurements as well. Compared to natural gas or methane, n-heptane shows a lower sensitivity of CH*/OH* to changes in ϕ . Previous work¹⁴ suggested

that C_2^*/OH^* is a more sensitive measure for higher order hydrocarbons.

In addition to giving local equivalence ratio, chemiluminescence was also shown to be an excellent approach for monitoring flame stability in combustors. Both OH and CH chemiluminescence were used to detect blowout precursors, which are localized (in time and space) extinction events that precede blowout.

These events were detected using thresholding, and were found to increase in number as LBO limit is approached. Thus, the more frequent occurrence of these events indicates a closer proximity to blowout. This method was found to give good LBO proximity warning in a variety of atmospheric pressure combustors, including a single-cup, annular section, liquid-fueled combustor. Fiber optic collection of the emissions has been used to demonstrate the practicality of these methods for application in industrial and aircraft turbine engine combustors.

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REFERENCES

- ¹Gaydon, A.G. and Wolfhard, H.G., "Flames: Their Structure, Radiation, and Temperature", Fourth edition, Chapman and Hall, 1978.
- ²Keller, J.O. and Saito, K., "Measurements of the Combusting Flow in a Pulse Combustor", *Combustion Science and Technology*, Vol. 53, 1987, pp. 137-163.
- ³Lawn, C.J., "Distributions of Instantaneous Heat Release by the Cross-Correlation of Chemiluminescent Emissions," *Combustion and Flame*, Vol. 132, 2000, pp. 227-240.
- ⁴Roby, 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.
- ⁵Mehta, 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.
- ⁶Najm, H. N., Paul, P.H., Mueller, C. J., and Wyckoff, P. S., "On adequacy of certain experimental observables as measurements of flame burning rate", *Combustion and Flame*, Vol 113, pp 312-332.
- ⁷Khanna, V. K., Vandsburger, U., Saunders W. R., Baumann, W. T., "Dynamic analysis of swirl stabilized turbulent gaseous flames", paper GT-2002-30061, Proceedings of ASME Turbo Expo 2002, Amsterdam, Netherlands, Jun 3-6, 2002.
- ⁸Ikeda, Y., Kojima, J., Nakajima, T., "Local Damkohler number measurement in turbulent methane/air premixed flames by local OH^* , CH^* and C_2^* chemiluminescence", paper AIAA-2000-3395, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Alabama, Jul 16-19, 2000.
- ⁹Kojima, J., Ikeda, Y., and Nakajima, T., "Spatially resolved measurement of OH^* , CH^* and C_2^* chemiluminescence in the reaction zone of laminar methane/air premixed flames", Twenty eighth Symposium (International) on Combustion, 2000, pp. 1757-1764.
- ¹⁰Higgins, B., McQuay, M. Q., Lacas, F., Rolon, J. C., Darabiha, N., Candel, S., "Systematic measurements of OH chemiluminescence for fuel-lean, high-pressure, premixed, laminar flames", *Fuel*, Vol. 80, 2001, pp 67-74.
- ¹¹Higgins, B., McQuay, M. Q., Lacas, F., and Candel, S., "An experimental study on the effect of pressure and strain rate on CH chemiluminescence of premixed fuel-lean methane/air flames", *Fuel*, Vol. 80, 2001, pp 1583-1591.
- ¹²Ikeda, Y., Kojima, J., Hashimoto, H., Nakajima, T., "Detailed local spectra measurement in high-pressure premixed laminar flame", paper AIAA-2002-0191, 40th Aerospace sciences meeting and exhibit, Reno, Nevada, Jan 14-17, 2002.
- ¹³Roby, 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, 593-602.
- ¹⁴Morrell, 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.

- ¹⁵Nicholson, 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.
- ¹⁶Longwell, J.P., Cheveney, J., Clark, W., and Frost, E., "Flame Stabilization by Baffles in a High Velocity Gas stream", *Third Symposium (international) on Combustion*, 1951.
- ¹⁷Williams, G.C., and Shipman, C.W., "Some Properties of Rod Stabilized Flames of Homogeneous Gas Mixtures", *Fourth Symposium (international) on Combustion*, 1953.
- ¹⁸Williams, G., Hottel, H., and Scurlock, A., "Flame Stabilization of Flames in High Speed Flows by Pilot Flames", *Seventh Symposium (International) on Combustion*, 1958.
- ¹⁹Hsu, K.-Y., Goss, L. P., Roquemore, W. M., "Characteristics of a trapped vortex combustor", *Journal of Propulsion and Power*, Vol. 14, No. 1, Jan-Feb 1998.
- ²⁰Carrier, G., Fendell, F., Sheffield, M., "Stabilization of premixed planar flame by localized energy addition", paper AIAA-89-0155, *27th Aerospace sciences meeting*, Reno, NV, Jan 9-12, 1989.
- ²¹Syred, N., and Beer, J. M., "Combustion in Swirling flows: A review", *Combustion and Flame*, Vol. 23, 1974, pp 143-201.
- ²²Durbin, M.D., and Ballal, D.R., "Studies of Lean Blowout in a Step Swirl Combustor", *Transactions of the ASME*, Vol. 118, 1996, pp 72-77.
- ²³Sturgess, G.J., Sloan, D.G., Roquemore, W.M., Shouse, D., Lesmerises, A.L., Ballal, D.R., Heneghan, S.P., Vangsness, M.D., and Hedman, P.O., "Flame Stability and Lean Blowout – A Research Program Progress Report", Paper No. 91-7037, *Proceedings of Tenth ISABE*, Nottingham, England, pp 372-384.
- ²⁴Chao, 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, pp. 335-342.
- ²⁵Hedman, 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 GT-2002-30052, *Proceedings of ASME TURBO EXPO 2002*, Jun 3-6, 2002, Amsterdam, Netherlands.
- ²⁶Bradley, D., Gaskell, P. H., Gu, X. J., Lawes, M., and Scott, M. J., "Premixed Turbulent flame instability and NO formation in a lean-burn swirl burner", *Combustion and Flame*, Vol. 115, 1998, pp. 515-538.
- ²⁷Chen, T. H., Goss, L. P., Talley, D., Mikolaitis, D., "Stabilization zone structure in jet diffusion flames from liftoff to blowout", paper AIAA-89-0153, *27th Aerospace Sciences Meeting*, Reno, NV, Jan 9-12, 1989.
- ²⁸Shih, W.-P., Lee, J. G., and Santavicca D. A., "Stability and emissions characteristics of a lean premixed gas turbine combustor", *Twenty Eighth Symposium (International) on Combustion*, 1996, pp. 2771-2778.
- ²⁹Roquemore, W. M., Reddy, V. K., Hedman, P. O., Post, M. E., Chen, T. H., Goss, L. P. Trump, D., Vilimpoc, V., and Sturgess, G. J., "Experimental and Theoretical studies in a Gas-fueled research combustor", paper AIAA-91-0639, *29th Aerospace Sciences Meeting*, Reno, NV, Jan 7-10, 1991.
- ³⁰Gutmark, E., Parr, T. P., Hanson-Parr, D. M., Schadow, K. C., "Simultaneous OH and Schlieren visualization of premixed flames at the lean blow-out limit", *Experiments in fluids*, Vol 12, pp 10-16, 1991.
- ³¹Muruganandam, 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.
- ³²Gupta, A.K., Lilley, D.G., and Syred, N., "Swirl Flows", Abacus Press, Kent, England, 1984.
- ³³Bellows, B.D., Zhang, Q., Neumeier, Y., Lieuwen, T., Zinn, B.T., "Forced Response Studies of a Premixed Flame to Flow Disturbances in a Gas Turbine Combustor", AIAA 2003-0824, 41st AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 2003.
- ³⁴Kappei, F., Lee, J. Y., Johnson, C. E., Lubarsky, E., Neumeier, Y., and Zinn, B. T., "Investigation of Oscillatory Combustion Processes in an Actively Controlled Liquid Fuel Combustor," Paper 2000-3348 AIAA/ASME/SAE/ASEE 36th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 16-19, 2000.