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# A COMBUSTION CONTROL AND DIAGNOSTICS SENSOR FOR GAS TURBINES

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## ABSTRACT

The implementation of sophisticated combustion control schemes in modern gas turbines is motivated by the desire to maximize thermodynamic efficiency while meeting NOx emission restrictions. To achieve target $NO_X$ levels, modern turbine combustors must operate with a finely controlled fuel-air ratio near the fuel-lean flame extinction limit, where the combustor is most susceptible to instabilities. In turbine configurations with multiple combustors arranged around the annulus, differences in flow splits caused by manufacturing variations or engine wear can compromise engine performance. Optimal combustion control is also complicated by changes in environmental conditions, fuel-quality, or fuel-type. As a consequence, engines must be commissioned in the field with adequate stability margin such that manufacturing tolerances, normally expected component wear, fuel-quality, and environmental conditions will not cause unstable combustion.

A lack of robust combustion in-situ monitoring has limited the ability of modern turbines to achieve stable ultra-low emission performance over the entire load range. This paper describes a combustion control and diagnostics sensor (CCADS) that can potentially revolutionize the manner in which modern gas turbines are controlled. This robust sensor uses the electrical properties of the flame to detect key events and monitor critical operating parameters within the combustor. The CCADS is integrated into the fuel nozzle such that low cost and long life are achieved. Tests conducted at turbine conditions in laboratory combustors instrumented with CCADS have demonstrated the following potential capabilities: 1) detection of *incipient* flashback and auto-ignition 2) detection of *incipient* lean blowout 3) detection of dynamic pressure oscillations 4) and a qualitative measure of equivalence ratio within the combustor. Many of these capabilities have been reported in other publications with data from an atmospheric combustion rig. This paper will summarize each of the capabilities with recent data at turbine conditions. The expectation is that CCADS will provide the key in-situ monitoring for diagnostics and control of modern gas turbines, allowing them to achieve stable ultra-low emissions performance.

## INTRODUCTION

Some low-emission industrial gas turbines are successfully meeting NOx emission goals of less than 10 ppm at full load, yet operational concerns limit emission performance at part-load, start-up, and shutdown conditions[1]. To achieve target $NO_X$ levels, modern turbine combustors must operate with a finely controlled fuel-air ratio near the flame extinction limit. Unfortunately, this is also where the combustor is most susceptible to operational concerns such as combustion dynamics, flashback, loss of flame anchor, and lean blowout. A thorough article by Richards et al.[2] discusses these concerns and other associated issues for lean premix (LPM) combustors in gas turbines. However, achieving low exhaust emissions is secondary to the reliability and durability of the engine, which can be compromised by the noted operational concerns. Sophisticated control strategies and design changes have been implemented with the goal of maintaining low exhaust emissions, while providing the robust operability to protect the hot gas path components both upstream and downstream of the combustor. A good example is Myers et al.[3] discussion of a state-of-the-art H-

Class industrial gas turbine. Robust operability of an engine is achieved by maintaining a wide operating margin away from the lean blowout limit. A reluctance to minimize the stability margin stems from a lack of in-situ real-time combustion monitoring, and the many factors that can change the lean blowout limit during operations including component wear, daily environmental changes, and fuel-quality[2]. This issue is further complicated by component size variations due to manufacturing tolerances, which can result in each of the local combustor having different apparent lean blowout limits. These issues coupled with the expectations of more stringent emission regulations have increased interest in sensors for local combustion monitoring and control.

There are a variety of methods that have been proposed to both sense combustion and optimize operating conditions. Docquier and Candel[4] provide an excellent review of the subject. Laboratory tests have demonstrated the performance advantages of combustion control for reducing emissions[5,6,7]. For complete gas turbine engines, Corbett and Lines[8] discuss the various control parameters required to produce very-low emissions. The absence of a reliable sensor to directly monitor conditions in the combustor requires the addition of numerous indirect sensors for flow rates, inlet humidity, etc. Pandalai and Mongia[9] note the importance of sensing lean blowout and combustion dynamics, and discuss corrective control actions by re-directing fuel flow to various regions of the combustion chamber. In this example, combustion dynamics are monitored using high frequency pressure transducers. Nair and Lieuwen[10] also describe a technique to determine incipient blowout using the flame acoustic signature. One disadvantage of using high frequency pressure transducers is the difficulty of measuring local conditions in a specific combustor can.

Various authors have investigated the use of optical methods to determine fuel-air ratio, and measure fluctuating heat release or fuel-air ratio that drive combustion dynamics[11,12,13]. Others have developed optical sensor techniques for detecting *incipient* lean-blowout[14]. Optical sensors have the advantage of avoiding direct contact with the high-temperature combustion products, but are limited to sensing conditions along an available line-of-sight. In order to incorporate these optical methods in potential gas turbine applications, both the pressure-casing and combustion liner must be penetrated. Nevertheless, optical flame sensors detecting flame chemiluminescence are now available[15], and are used as part of the feedback control system in gas turbines.

An alternative to optical sensing is to use flame ionization signals as an indicator of combustion conditions. Flame ionization probes exhibit high frequency response characteristics similar to optical techniques. Furthermore, flame ionization probes do not require adding line-of-sight access to the combustion region, and the signal can be collected from a single wire. This paper describes a combustion control and diagnostics sensor (CCADS) that can potentially revolutionize the manner in which modern gas turbines are controlled. Tests conducted at turbine conditions in laboratory combustors instrumented with CCADS have demonstrated the following potential capabilities: 1) detection of *incipient* flashback and auto-ignition 2) detection of *incipient* lean blowout 3) detection of dynamic pressure oscillations 4) and a qualitative measure of equivalence ratio within the combustor. The expectation is that CCADS will provide the key in-situ monitoring for diagnostics and control of modern gas turbines, allowing them to achieve stable ultra-low emissions performance.

## FLAME IONIZATION BACKGROUND

The presence of ions in flames has been known for well over a century. Volumes of literature exist on the subject of flame ionization, including descriptions of the mechanisms for the ion formation and the electrical properties of the flame[16,17]. Calcote[16] and Fialkov[17] have written thorough review articles on this subject, and it is widely accepted that the key mechanism enabling the flow of electrical current through hydrocarbon flames results from the chemi-ionization of the formyl radical, CHO*:

$$CH + O \rightarrow CHO^* \rightarrow CHO^+ + e^- \qquad (1)$$

The resulting electrical properties of the flame have enabled several practical applications including hydrocarbon analyzers, flame detectors, flame speed detectors[18], flame stabilization[19], and even flame tomography[20]. A typical flame ionization sensing technique consists of at least two electrodes arranged such that a voltage potential can be applied across the flame, or a part of the flame. The electrical properties of the flame facilitate a measurable current that is related to a parameter of interest. For example, a typical flame ionization detector (FID) used in a hydrocarbon analyzer has electrodes arranged such that a voltage potential is applied across the entire flame, and the amount of electrical current flow through the flame is linearly proportional to the hydrocarbon concentration[21].

In spite of this successful history, the use of flame ionization sensing for gas turbine applications has only recently been explored. In the past three years, the present authors have reported on the development of a combustion control and diagnostic sensor (CCADS)[22,23,24,25]. The CCADS design, summarized in the next section, offers a unique multi-function sensor capability. This unique capability coupled with a durable and simple design has increased commercial interest in CCADS for gas turbine applications. A commercial prototype CCADS has been developed and tested under a Cooperative Research and Development Agreement (CRADA) between the National Energy Technology Laboratory (NETL) and Woodward Industrial Controls. A series of experimental tests using the test rig and CCADS hardware described in Benson et al.[25], have been conducted at representative turbine operating conditions. These data will be examined in this paper for specific applicability to the operational concerns related to LPM combustors: 1) flashback and auto-ignition, 2) lean blowout, 3) dynamic pressure oscillations, and 4) equivalence ratio.

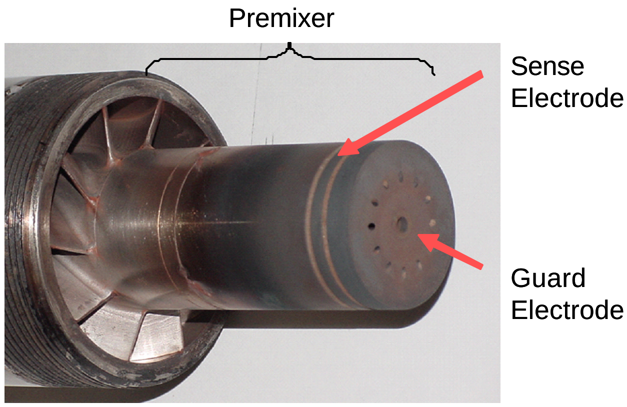


**Figure 1: Photo of Lab-Scale CCADS Nozzle**

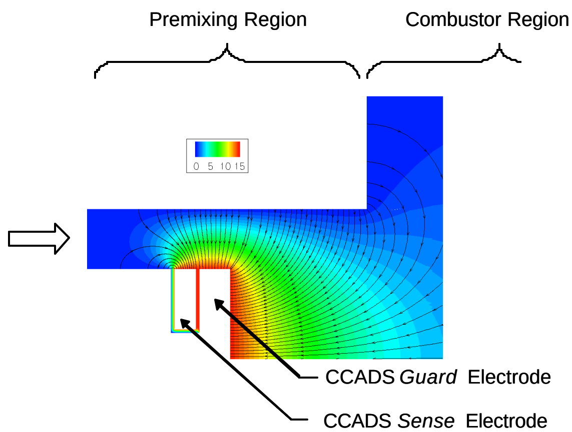


**Figure 2: Two-dimensional Simulation of Potential Gradient**

## SENSOR DESCRIPTION

The CCADS technique is based on two electrically isolated electrodes installed on the center-body of the premix nozzle, as shown in Fig. 1. The electrode closest to the combustion zone is called the *guard* electrode, and the electrode upstream of the *guard* is called the *sense* electrode. When an equal-potential voltage is applied to both electrodes, this novel electrode arrangement facilitates current flow from the *guard* electrode through the flame. On the other hand, a significant ionization current from the *sense* electrode is produced only when the flame enters the premixing region of the fuel injector (i.e., auto-ignition, and flashback). A two-dimensional electrostatic FLUENT simulation of the electrode configuration is shown in Fig. 2. The potential gradient lines shown in Fig. 2 are expected to be similar to the prototype CCADS sensor.

## EXPERIMENTAL SETUP

The combustion rig, instrumentation, and data acquisition is identical to the setup described in Benson et al.,[25]. A cross-section of the test rig is shown in Fig. 3. Preheated air enters the plenum region from metered high temperature flow loops. All flow measurements (fuel and air) are within two-percent of flow standards. Fuel and air are mixed inside the premix nozzle prior to entering the water-cooled combustion region. A cylindrical centerbody that is situated along the axis of the premixer also supports two electrodes as shown in Figures 1 and 2. For the data described in this paper, the entire combustor is grounded and the electrodes are electrically isolated from the combustor hardware. A series of two evaluations of CCADS have been conducted using the test conditions described in the next section. In the first evaluation, the test rig is identical to the experimental setup described in Benson et al.[25]. For the second evaluation the removable plug shown in Fig. 3 has

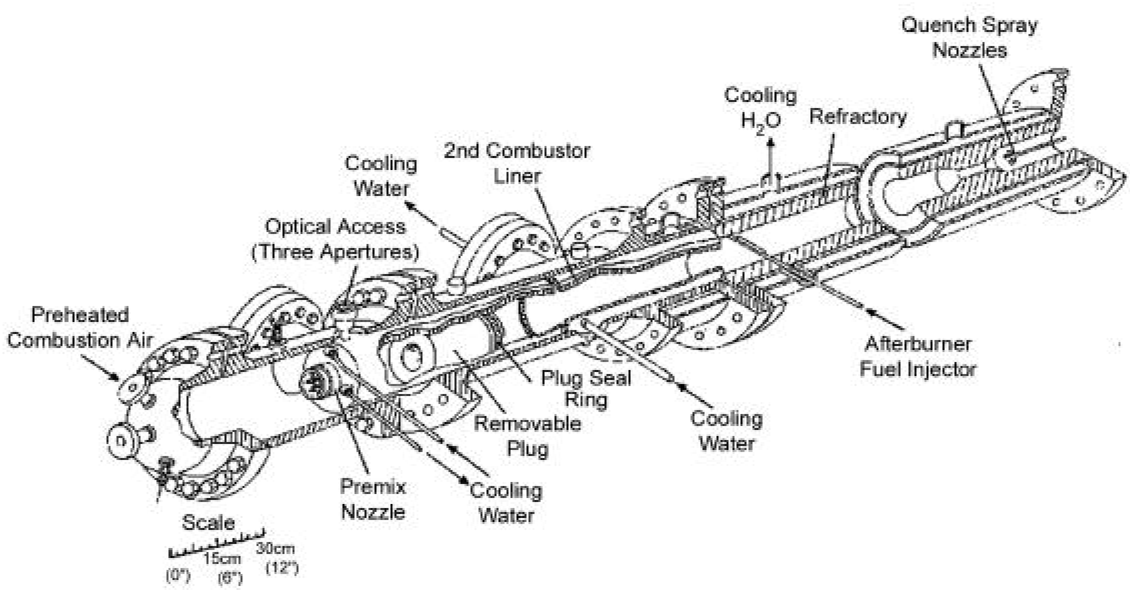


**Figure 3: Cross-section of Experimental Combustion Test Rig**

been relocated to extend the length of the combustion zone from 0.20 meters to 0.91 meters. This modification reduces the magnitude of dynamic pressure oscillations observed during the first evaluation.

## TEST RESULTS

The data discussed in this section have been obtained at conditions listed in Table 1. During all tests, the inlet-air temperature is maintained at 589°K (600°F). The test matrix shown in Table 1 is designed to analyze the effects of operating pressure, equivalence ratio, and bulk flow velocity on the CCADS guard signal. Unfortunately, the statistical analysis of these operating conditions has been biased by the effects of large dynamic pressure oscillations and incipient lean blowout (LBO) events. It is important to note, however, that the sensitivity of the CCADS signal to dynamic pressure oscillations, incipient LBO events, and incipient flashback events may be advantageous from a diagnostic sensor perspective. This will be discussed more thoroughly in the next sections.

**Table 1: Matrix of Test Conditions**

| Test Condition | Nozzle Velocity (m/s) | Pressure (kPa) | Equivalence Ratio |
|---|---|---|---|
| 1 | 60 | 506.8 | 0.600 |
| 2 | 67.5 | 633.3 | 0.550 |
| 3 | 75 | 506.8 | 0.500 |
| 4 | 75 | 759.8 | 0.500 |
| 5 | 67.5 | 633.3 | 0.550 |
| 6 | 75 | 506.8 | 0.550 |
| 7 | 75 | 759.8 | 0.600 |
| 8 | 60 | 759.8 | 0.550 |
| 9 | 60 | 506.8 | 0.550 |
| 10 | 60 | 759.8 | 0.600 |
| 11 | 60 | 759.8 | 0.500 |
| 12 | 67.5 | 633.3 | 0.550 |
| 13 | 75 | 759.8 | 0.550 |
| 14 | 75 | 506.8 | 0.600 |
| 15 | 60 | 506.8 | 0.500 |
| 16 | 67.5 | 633.3 | 0.550 |

The test data summary in Fig. 4a and Fig. 4b show the average current through the guard *electrode* at each operating condition. Figure 4a shows the data from the 0.20m combustor length, and Fig. 4b shows the data from the 0.91m combustor length. These average ionization current data are collected for a +100 VDC potential applied to both electrodes.

The measurements from the short combustor are characterized by large dynamic pressure oscillations, which affected repeatability at the center-point and other conditions within the matrix. A boundary between stable and oscillating combustion coincidentally occurred near the center-point in the test matrix, meaning that the pressure amplitude is very sensitive to slight changes in operating conditions. This will be described in more detail in a later section.

To improve combustion stability, the combustion chamber length is changed from 0.20m to 0.91m. The results shown in Fig. 4b have much better repeatability at the center-point. However, at higher bulk flow velocities (i.e., 75 m/s) and lower equivalence ratios *incipient* LBO occurs. These *incipient* LBO events cause large variations in the ionization current and bias any statistical analysis for these test conditions.

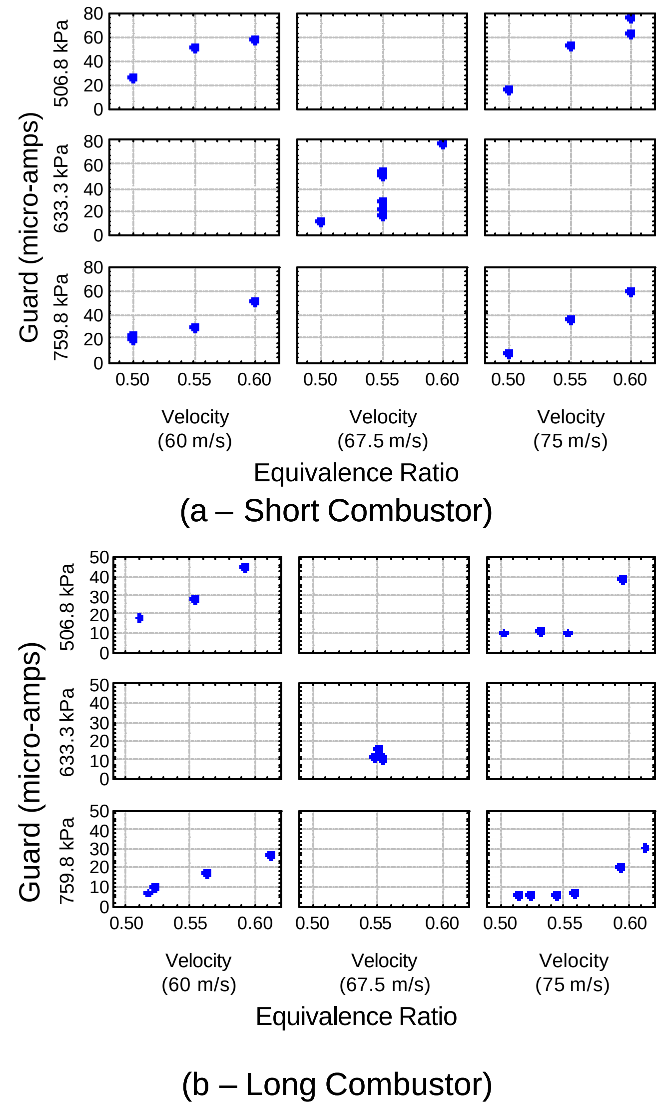


**Figure 4: Average Guard Current as a Function of Operating Pressure, Bulk Velocity, and Equivalence Ratio. Data are collected with +100 VDC potential applied to both electrodes.**

The following sections will discuss how the real-time data can be used to detect the adverse conditions (i.e., flashback, LBO, dynamics), and serve as a multi-function sensor for diagnostics and control in gas turbines.

## FLASHBACK AND AUTO-IGNITION

The most desirable capability of a flashback detection sensor is to detect *incipient* flashback, and provide adequate response such that flashback mitigation can be achieved. In this discussion, *incipient* flashback is defined as an instantaneous re-location of the reaction zone into the premixing region. Keller et al.[26] have shown how dynamic instabilities can trigger flame flashback in a step stabilized combustor. Flames periodically enter the premixer and result in localized hot-spots that can lead to either a slow 'creep' of the flame anchor along the centerbody, or a fast transition of the flame anchor into the premixer. In either case, the resulting hardware failures need no further elaboration. The data discussed in this section show the CCADS capability to detect *incipient* flashback and perform self-diagnostics during normal operations.

The novel cylindrical electrode configuration of CCADS provides 360° sensing circumferentially and axially along the entire premixed section. This eliminates the uncertainty associated with using line-of-sight or local measurements to detect flashback and auto-ignition. As described earlier, the electrode closest to the combustion zone is called the *guard* electrode, and the upstream electrode is called the *sense* electrode. For the remainder of the results described in this paper, the potential on the electrodes is kept at +15 VDC. Although higher voltages can be applied to the electrodes, these typical instrumentation voltages provide adequate signal-to-noise ratio to obtain good information about the flame behavior.

The electrodes are arranged to prevent the turbulent flame in the combustion zone from causing a false indication of flashback on the *sense* electrode circuit. Figure 2 shows the shape of the electric field when both electrodes are maintained at the same voltage potential (i.e., +15 VDC). It should be noted that the potential gradient lines from the *guard* electrode extend into the flame region, whereas, the lines from the *sense* electrode do not. Therefore, negative ions and electrons in the flame region will be preferentially attracted to the *guard* electrode.

On the other hand, the *sense* electrode is essentially isolated from the combustion zone. Therefore, any ions and/or electrons that are generated in the premixer region will generate a current in the *sense* electrode circuit. This isolation effect is demonstrated by the data shown in Fig. 5. If the potential on the *guard* electrode is suddenly removed, the average signal collected by the *sense* electrode increases. The fact that the signal from the *sense* electrode does not reach the same level as the *guard* electrode signal indicates the importance of the electrode position and the importance of the electric field shape.

It is believed that the procedure described in the previous paragraph could be used as a self-diagnostic method to test the functionality of the CCADS circuitry. Self-diagnostic capability is an important feature, especially for sensors used for critical event detection such as flashback and auto-ignition. Without the ability to verify the operation of a flashback detection system, implementation is unlikely due to the huge consequences associated with a sensor failure. If the voltage is momentarily removed from the guard electrode, an increase in current through the sense electrode can verify operability of the flashback and auto-ignition functions of CCADS during normal operations. This type of self-diagnostic test can be easily implemented into the CCADS electronic interface. Secondly, the sense electrode also serves as a redundant sensor for main chamber combustion monitoring, should the guard electrode fail.

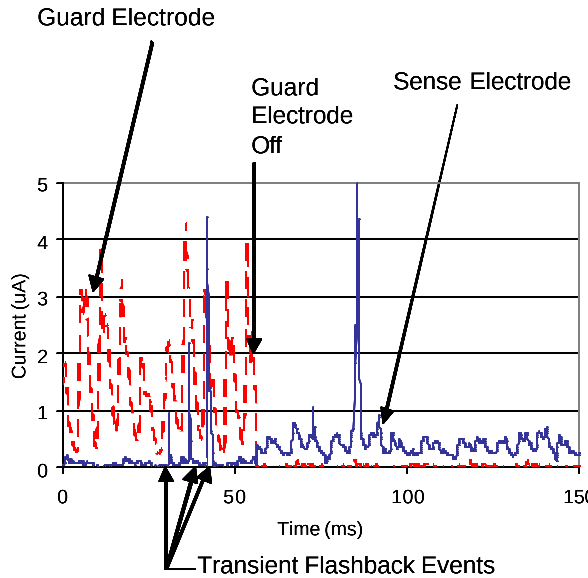


**Figure 5: Data Showing The Effect of the Guard Voltage Bias on the Sense Electrode Signal**

The data in Fig. 5 also show that the sensor can reliably detect even transient excursions of flames inside the premixer. At this operating condition, the large dynamic pressure oscillations cause localized flow reversal near the walls and result in the flame momentarily entering the premixer. Even at very fuel-lean conditions, a significant amount of current is measured through both the guard and sense electrodes. The fast response of CCADS provides the capability to detect *incipient* flashback events that can facilitate corrective actions prior to hardware damage. It is important to note that specific flashback and auto-ignition conditions have not been tested (i.e. flame anchoring inside the premixer) due to concern of hardware damage at these conditions. However, the data in Benson et al.,[25] demonstrate this capability at similar conditions in which an offset in *sense* current indicates that the flame has attached inside the premixer. Furthermore, it is well documented that ions exist well downstream of the flame front[17]. Therefore, the authors feel it is reasonable to suggest that a flame anchored anywhere within the premixing region will produce ions along the axis of the premixer. These ions will be detected by the *sense* electrode circuit.

For flashback detection the measured current through the *guard* electrode is not used. However, in the next sections data will be presented that show how the measured current through the *guard* electrode can also be utilized to provide the multi-function sensor capabilities described earlier.

## LEAN BLOWOUT

Detecting lean blowout is straightforward for sensor techniques, such as CCADS, where the signal is dependent on the presence of a flame. Obviously, when the flame is extinguished there is no signal. This section will show how CCADS can potentially be used to detect *incipient* blowout events, so mitigating action can be taken to prevent lean blowout (LBO) and the resulting consequences. Most LPM combustors are designed so the flame is aerodynamically anchored at the step expansion. As the combustor approaches LBO, momentary flame extinction and re-ignition events occur. The frequency of these events increase as the combustor get closer to LBO[10,14].

These precursor events can dramatically affect the measured current through the *guard* electrode. The data shown in Fig. 6 represents the average and standard deviation of the guard electrode signal for a range of equivalence ratio conditions in the flame. The data in Fig. 6 are calculated using a 250 milli-second time window, and the data sampling rate is 24,000 samples-per-second. Some examples of the raw time-series data are shown in Fig. 7. In any event, as the equivalence ratio decreases, the average current and the standard deviation of the current decrease until precursor LBO events begin to occur.

Figure 7 shows the raw data that is collected for a potential of +15 VDC applied to each of the electrodes. In Fig. 7b, a single precursor event can be seen in this 250 milli-second time period. As a result, the standard deviation of the guard electrode signal increases significantly. In fact, this operating point is shown in Fig. 6 as the point at which the standard deviation is larger than the average current.

If the equivalence ratio is decreased further, the number of LBO precursor events increase until the LBO limit is reached. Figure 8 shows the time series data very close to the LBO limit. It is important to note that due to the relatively long time-scale required to re-ignite the flame at these lean conditions, the actual number of precursor events-per-second may actually decrease prior to LBO.

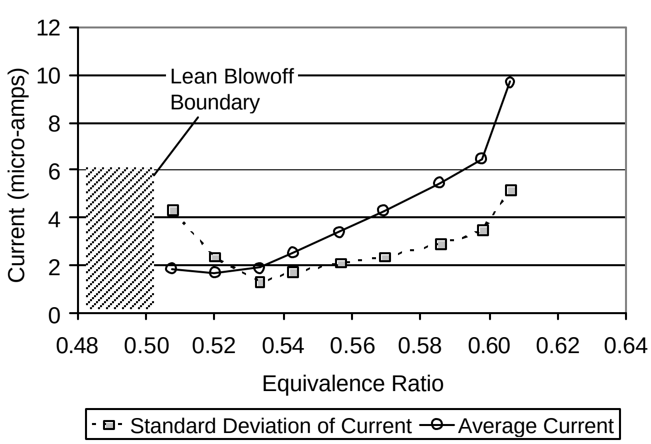


**Figure 6: Standard Deviation and Average Guard Current as a Function of Equivalence Ratio.**

The fast response and the sensitivity of the CCADS concept make this approach attractive for flame blow-off detection. However, in order to detect other features of the flame, such as dynamic pressure and local fuel-air ratio, the flame ionization signal needs to be analyzed differently. It may be necessary to incorporate some logic, or hierarchal structure in the control scheme to realize this multi-function capability. This will be described in the following paragraphs.

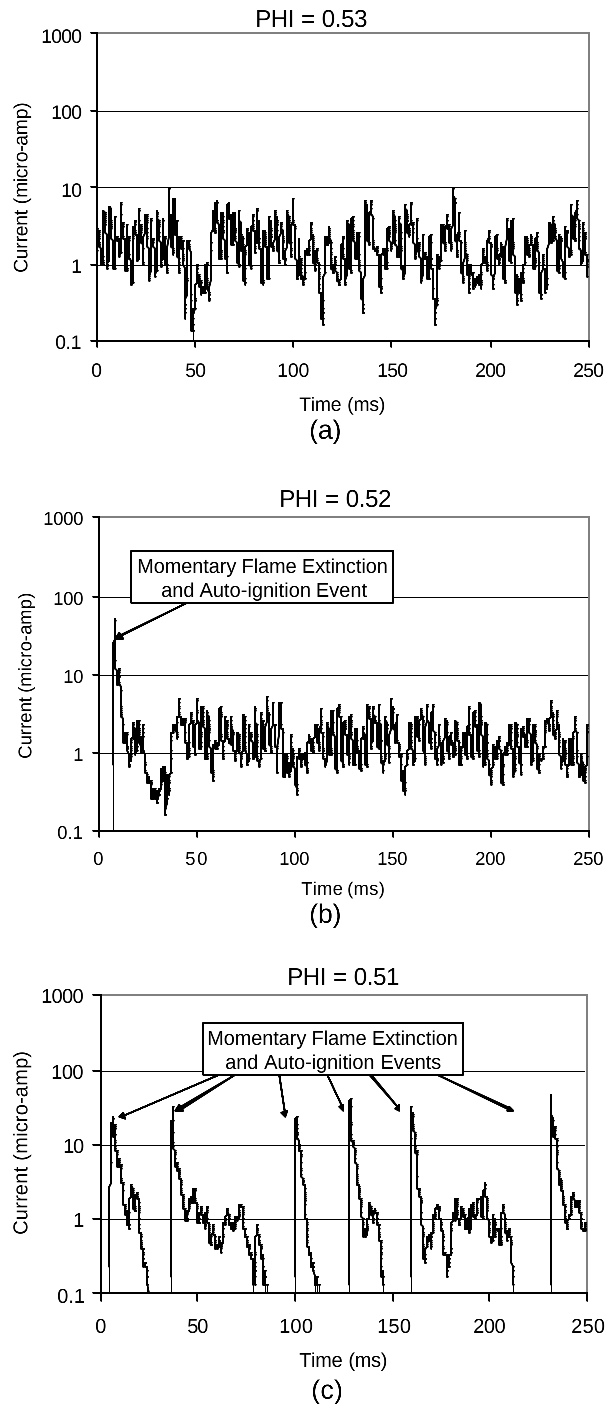


**Figure 7: Figure 7: Time-Series Data Showing Guard Current as the Equivalence Ratio is Decreased.**

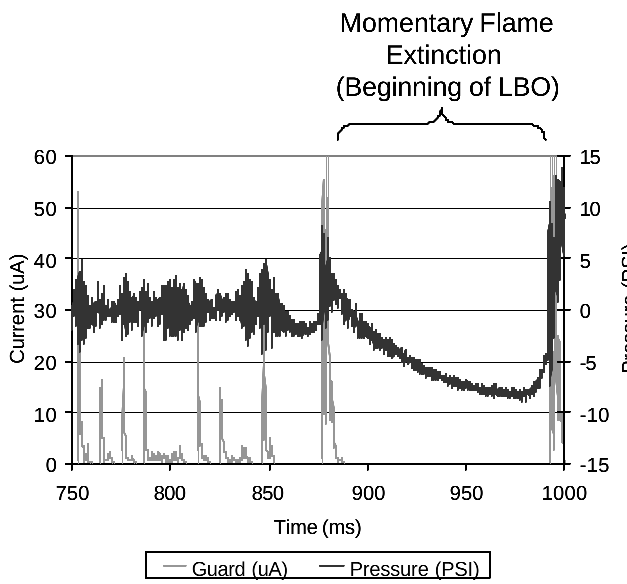


**Figure 8: Pressure and Flame Ionization Current Data Showing the Initiation of Lean Blowout**

## DYNAMIC PRESSURE

The vibration and heat transfer caused by dynamic pressure oscillations can lead to combustion hardware failure. Therefore, pressure oscillations in gas turbines are currently monitored using a dynamic pressure transducer. The data presented in Benson et al.,[25] show a good agreement between the frequency content of the CCADS *guard* signal and the dynamic pressure transducer signal. These data also indicate that periodic excursions of the flame into the premixer do not mask (obscure) the primary pressure frequency from the current signal. This section will discuss the potential for also using the CCADS to monitor combustion dynamics, during otherwise normal operating conditions. In other words, when the CCADS does not indicate *incipient* flashback, or LBO, the *guard* signal can be used to ascertain useful information about dynamic pressure.

The data in Fig. 9 show the standard deviation of the *guard* signal and the standard deviation of the dynamic pressure transducer signal at the center-point of the experimental test matrix (i.e., Conditions 2, 5, 12, and 16 in Table 1). Although the data shown in Fig. 9 are from the short combustor configuration (i.e., Fig. 4a), the longer combustor configuration data show a similar trend. It should be noted that although the air flow rate, fuel flow rate, and average combustor pressure are approximately the same for all of the data shown in Fig. 9, this operating condition is near a stability boundary, so a reasonably wide range of dynamic pressure amplitudes are observed. It should be noted that hysterese effects are commonly observed in combustion oscillations[27], particularly near stability boundaries. Therefore, depending on the direction from which the stability boundary is approached, the magnitude of the oscillation can vary considerably for the same operating condition. In any event, the data in Fig. 9 suggest that a monotonic relationship exists between the standard deviation of the *guard* signal and the standard deviation of dynamic pressure measurements. However, this correlation can be complicated by incipient flashback or LBO events in the signal. More data analysis is underway that can potentially define this relationship.

Although more work in this area is needed, it is believed that the onset of combustion dynamics during normal operations can be determined by an increase in the standard deviation of the *guard* signal. It has been demonstrated[25] that the frequency of oscillations can be obtained from the guard signal, even during *incipient* flashback conditions. To use CCADS as a multi-function sensor a hierarchal structure for evaluating the data, based on the importance, must be established. For example, the average and standard deviation for both the *guard* and *sense* electrode could be computed on a continuous basis. Depending on the order of importance, these quantities could be evaluated at the desired interval to detect LBO or flashback events. If LBO or flashback events do not exist, the data is useful for evaluating the dynamic pressure. This hierarchal approach seems reasonable, since the conditions of LBO and flashback require immediate control action to mitigate the undesirable operating condition, regardless of the dynamic pressure characteristics.

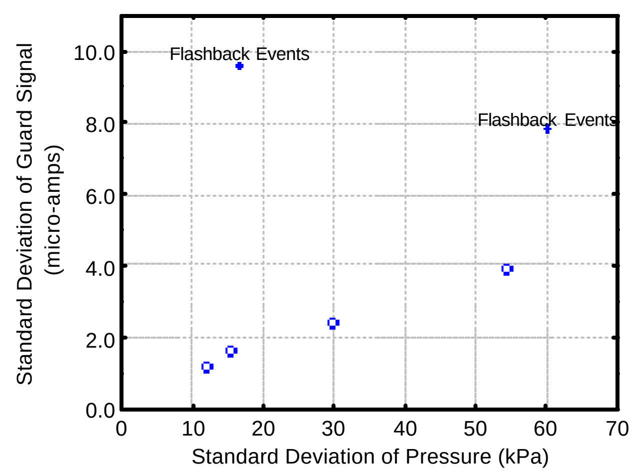


**Figure 9: Comparison of Variations in the Flame Ionization Signal With Variations in the Dynamic Pressure For Constant Operating Conditions**

## EQUIVALENCE RATIO

Using CCADS to determine a quantitative equivalence ratio measurement may be significantly influenced by other combustion phenomena that can occur in a turbulent combustion region, many of which have been described in this paper. However, operating experience in the laboratory has shown the ability of CCADS to provide a qualitative measure for controlling the local equivalence ratio at a stable low-emission level. This qualitative measurement may also be used to balance individual fuel injectors, for example, around an annular combustor.

 

The data in Fig. 6 show the average guard current as a function of the equivalence ratio. If the fuel-lean conditions that produced precursors to LBO, and the fuel-rich conditions that produce significant pressure oscillations are ignored, there is a good correlation between equivalence ratio and guard current. In the normal operating region the relationship between equivalence ratio and the average *guard* current is linear, so why not develop a reasonably accurate quantitative measure of equivalence ratio? That question can only be answered by the end user, who would have to characterize the equivalence ratio and average *guard* current for their specific rig configuration.

A more important issue is how to use the average *guard* current during normal operations to control the combustion system. As shown in Fig. 6 the *guard* current decreases with equivalence ratio, a reasonable strategy for ultra low-emission operations is to control each fuel nozzle to the minimum average guard current on the desirable side of the boundary where precursors to LBO are observed. It is important to note that the fuel and/or air flow to the local combustors must be independently controlled to balance the system using this method.

## CONCLUSIONS

A lack of robust combustion in-situ monitoring has limited the ability of modern turbines to achieve stable ultra-low emission performance over the entire load range. This paper describes a combustion control and diagnostics sensor (CCADS) that can potentially revolutionize the manner in which modern gas turbines are controlled. This sensor uses the electrical properties of the flame to detect key events and monitor critical operating parameters within the combustor. The potential capability of CCADS to provide the following types of information has been discussed:

1) Detection of *incipient* flashback and auto-ignition,

2) Detection of *incipient* lean blowout,

3) Detection of dynamic pressure oscillations, and

4) Qualitative measure of equivalence ratio.

In addition, a CCADS in-situ self-diagnostics method which can ensure sensor reliability has also been discussed. The expectation is that CCADS will provide the key in-situ monitoring for diagnostics and control of modern gas turbines, allowing them to achieve stable ultra-low emissions performance.

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