Sensor Response and Sensor Network Development for Practical Combustors

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Abstract—**Meeting environmentally benign clean energy demands with expected growing population in the near term requires the development of smarter combustors and power plants. The future power plants will need to be more efficient and emit near zero emissions. This will require a significantly improved real-time control and analysis system. A single sensor from a combustor or any component in a power plant unit provides inadequate information about the fate of various ongoing processes within the system. We envision that future advanced power plants will have a large number of sensors to provide comprehensive information about the fate of various ongoing processes in the combustion system. Incorporating a large number of sensors in a sensor network will allow one to obtain comprehensive information, which can then be processed to visually display the detailed behavior in real time and support advanced control systems that can formulate the plant behavior. In this paper, we provide systematic development of a single sensor response from a combustor to understand the sensor's response on location and operational parameters. The results reveal the need for multiple sensor arrays for detailed visualization, analysis, and process control. These results will be used as a guideline for determining the type and nature of high density sensor network around the combustor of a power plant. Different issues and algorithms about high-density sensor networks in advanced combustors are also discussed.**

Keywords-component; Sensors, Networks, Combustors

I. INTRODUCTION

Next generation of advanced combustors will be smarter with many control functions, provide significantly higher efficiency and performance, and result in near-zero emissions of harmful pollutants, including the carbon emissions. In seeking optimum system performance in advanced combustor design, the challenges of local flow, pressure, chemical composition and thermal signatures, as well as their interactions, are complex issues to consider. The main problem in effectively controlling operational performance lies in determining the actual conditions within the combustor and other components in the system (e.g., turbine, heat exchangers, fans and pumps), both in time and space. This is particularly true when there are thermal load variations or with dual fuel combustors.

Sensors are critical elements in combustion control and monitoring to create a more efficient and robust combustion system. If one or two sensors were to be used in the combustion zone or tunnel, their numerical values would more likely be questionable because the local value of a given parameter (for example, temperature, pressure, species concentration, velocity, density, fuel/air mixture ratio) may not represent the actual behavior in the combustor. With rapidly approaching revolutions in sensing and control, incorporating a high-density sensor network with a large number of sensor arrays one can seek attractive benefits for smarter combustor development, with initial specific goal of detailed information about the various ongoing processes within the system. Although the flood of data from a large number of sensors may challenge our ability to handle and process data, this may potentially change the manner in which sensors are used to control the combustion process. Therefore, determining the appropriate number of sensors and their locations in a practical combustor is important. Also important is determining the interaction of plant operator and engineers with the sensor data and their implementation. Currently, very little is known about the number of sensors that must be used for providing adequate and effective information from combustors or power systems. Furthermore, the critical locations for these sensors to provide representative information are not known. In addition, too many sensors may cause a flood of data that can challenge the ability of engineers to handle and process data, and thus may change the manner in which sensors are used to control the combustion process. Therefore, a self-organized sensor network, including lead sensor notes and other sensors as swarms or small groups rather than as individual sensors, may play an important role in advanced combustor design. It is likely that the sensors in such networks will work together to handle discrete tasks in the sensing and control network.

In this paper, we focus our efforts on seeking detailed information about spatial and temporal signatures from a practical combustor from the point of view of both sensor response and sensor networks. To achieve fundamental understanding of the influence of the sensor location on sensor readings, combustion roar and the associated instability signature have been chosen as the initial representative parameter (in reality, one has to monitor several other parameters to monitor the actual performance). The selected sensors, their relative positions within or around the combustor walls or adjacent to the walls are considered for

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Sponsor: US Dept of Energy

1-4244-1251-X/07/$25.00 2007 IEEE.

follow-up issues and algorithms associated with their use in a high-density sensor network in advanced combustors or power plants.

II. COMBUSTION BEHAVIOR

Combustion behavior is very complex in almost all practical power plant systems. The combustor performance is dictated by many parameters that a combustion process must incorporate and also by the fate of many ongoing complex processes in the system. Figure 1 illustrates combustion roar and combustion instability from a simple experimental combustion test rig and reveals that ordered pressure waves affect the combustor performance inside the combustion zone and past it into the combustion tunnel. Clearly, if one or two sensors were used in the combustion zone or the combustion tunnel, their numerical values would be erroneous because the local value of a given parameter would not provide the actual representative behavior in the combustor. Thus, if one considers a practical combustion system, the challenges of local flow, pressure, chemical composition, and thermal signatures are far more complex to find a potential optimum solution for the desired system performance.

III. SENSOR CONSIDERATIONS

The combustor used in this study is designed to operate over a wide range of conditions to allow examination of the different sensors under consideration. To realize an effective, high-density, heterogeneous sensor system, the following two fundamental issues need to be addressed: i) the desired parameters to be measured, and ii) the types of sensors that need to be used. The first issue has been addressed in the literature[1-5]. Some of these parameters include fuel concentration, fuel-to-air ratio, temperature, pressure, flow dynamics, and residual gas concentration[1]. Simultaneous information on the above parameters is often desirable. Due to the hostile conditions prevailing in combustors, the selected sensors should be able to withstand exposure to a harsh combusting environment. In addition, the sensor size selection must be based on the spatial variations in the flow and thermal structures so that the sensor can provide fast response at high frequency, thus allowing monitoring of relatively fast transient processes. Therefore, sensor selection is critical. In the following section, we discuss some sensors for possible use.

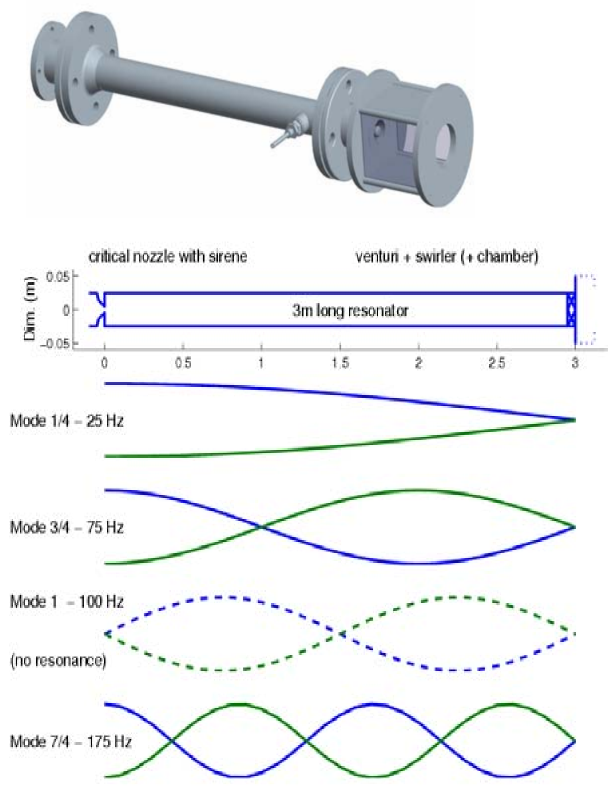


Figure 1. An experimental combustor with various modes of pressure waves inside the tube.

Optical absorption and emission sensors: Diode laser-based absorption and emission sensors have been well demonstrated for in-situ measurements in the flame region or in exhaust gases to detect major combustion species, such as H_2O, CO_2, and O_2. Such sensor types have also been developed and used for the measurement of gas temperature, velocity, and pressure[6,7]. However, the method only allows line-of-sight detection and provides mainly qualitative (or limited quantitative) information with little spatial resolution. It is important to note that both spatial and temporal resolutions are critical in combustion systems for seeking detailed information in the ongoing complex chemical processes and then using this information to provide the desired combustion control. Performance parameters need to be measured in terms of global emissions and exhaust gas signatures from the combustion process. In this respect, the current optical sensors based on line-of-sight methods might lead to low accuracy for evaluating highly non-homogenous flow.

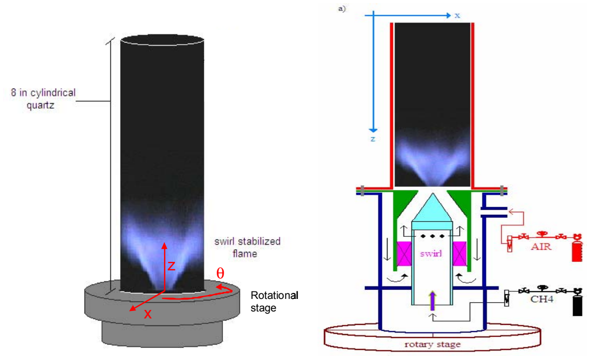
Fiber optic sensors: Fiber optic sensors have proven successful for measurements in harsh environments[8-10]. These sensors possess the advantages of lightweight, high sensitivity, invulnerability to electromagnetic interference (EMI), remote sensing capabilities, and multiplexibility[11]. Many of these sensors are made intrinsically within the optical fibers, and thus, the size (diameter) of these sensors is on the order of microscale. Fiber optic sensors have been demonstrated to provide measurement of temperature, pressure, gas concentration, and other key parameters to monitor details of the combustion process[9-11]. Owing to the remote sensing capabilities of fiber optic sensors, passive measurements can be realized in harsh environments. These sensors can be fabricated by using single crystal sapphire fibers that can survive in high-temperature environments (greater than 2000˚C). We believe that the development of multiplexed microscale fiber optical sensors for various combustion parameter measurements will significantly advance the development of future combustor systems.

Nanoscale gas sensors: Recently, many different nanoscale structures have been proven to have gas sensing capabilities[12,13]. By taking advantage of these nanoscale sensor techniques, distributed semi-conducting nanoscale sensors can be developed to measure the concentration of O_2, CO, and H_2O via the conductance readings from each sensor. Although these species are not adequate for seeking details about the combustion process, they do reflect some insights into it. Challenges in deploying a large number of nanoscale sensors include reading the sensor data and accessing each sensor.

Heterogeneous sensor system: Since novel microscale and nanoscale sensors with improved performance are rapidly developing and starting to play more important roles in many applications, they are expected to have a significant impact on combustion process monitoring because fuels and energy continue to be of greater importance than ever before. Our envisioned high-density sensor networks in future combustors involve a variety of heterogeneous sensors, including novel microscale and nanoscale sensors for pressure, flow, and temperature, fuel fraction and various gas species concentration measurements. The heterogeneous sensor system can provide both complementary and competitive information about a combustion system. Complementary information refers to the measurements of different characteristics of the combustion process, while competitive information refers to the measurements of the same characteristic but from different sensor units. Such a heterogeneous sensor system can provide a more reliable view and a higher confidence level of the operational status of an advanced combustion unit and power plant system.

IV. SENSOR RESPONSE

Determining information on quantifying the number and location of sensors that adequately describe the exact performance of a practical combustion system is not trivial. Our approach to tackle this challenge is to initially select the available sensor(s) that can be used to describe the fate of ongoing phenomena inside a practical combustor, and provide information about the fate of combustor performance using information with single and multiple sensors. Acoustic pressure, including that of combustion noise, has been chosen as the initial representative signature parameter. To achieve fundamental understanding of the sensor location influence on sensor readings, acoustic measurements have been carried out at different vertical and radial locations immediately outside a test combustor.



(a) (b)

Figure 2. (a) Schematic of UMD test combustor and (b) detailed view of the UMD test stand.

The University of Maryland (UMD) 50 kW premixed test combustor, shown in Figures 2(a) and (b), features many of the key characteristics associated with the practical combustors and is used here for the experimental program. The combustor possesses many key elements that are critical for simulating the behavior of many practical combustion systems used in the power industry. The combustion chamber is 210 mm long with an inside diameter of 55 mm. A quartz tube, located in the downstream section of the combustor, provides full optical access to the combustor region. Combustion occurred at atmospheric pressure under semi-confined conditions. The premixed condition was achieved by injecting methane fuel at 100 mm upstream from the combustor inlet to assure adequate mixing between the fuel and air. The flame was stabilized using a cascade of six swirl vanes that can be given any desired swirl strength using a 30°, 45°, or 60° swirl vane angle to the main flow direction.

Our initial efforts have used a single sensor to determine the extent of spatial variations at different positions downstream from the combustor as well as the angular variation at any given axial position downstream from the flame anchoring location in the combustor. Sound pressure measurements have been obtained using a piezoelectric microphone sensor coupled to a spectrum analyzer. The analyzer records signal from the microphone and performs a fast Fourier transform (FFT) on the signal to convert it to frequency domain. The accuracy of the system is +/- 1.5 dB with frequency discrimination of +/- 1%. The sound pressure levels (as amplitude-frequency spectra) are measured from 20 to 20,000 Hz. The sound spectrum analysis was averaged over 10 seconds to get a mean value of the results. The goal here was to determine the extent of spatial and temporal variations in sound pressure levels around the combustor. A traversing mechanism was assembled to enable moving the microphone both axially and angularly relative to the fixed combustor. The arrangement provided 0.01" vertical resolution and 1° angular resolution.

The acoustic waves generated from the combustor lie mainly in the frequency range of 200 Hz to 1 kHz. Low frequencies are associated with the combustion roar (200–500 Hz) while the higher frequencies are associated with some modes of acoustic coupling, including the standing waves in the flow ducts. To determine how the combustion-generated acoustic waves are related to the variation of microphone's vertical position location, we initially focused on the near-field acoustic signatures downstream from the combustor exit. The vertical location of the microphone was therefore limited to within 1" (i.e., z <1") from the burner exit. The radial distance of the microphone from the combustor was fixed at 1". The sound levels were recorded starting from vertical position of z=0 to the combustor downstream location in increment of 0.025". Background sound pressure levels associated with air flow, exhaust fan operation and other sources were also recorded to form as baseline sound pressure levels.

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Differential sound pressure levels (SPLs) were determined by subtracting the air flow sound level from the total sound pressure level when the combustor was ignited. Since combustion noise is the initial focus here, we only show the sound spectra over the frequency range of 100 Hz to 1 kHz. Some representative spectra of differential SPL are shown in Fig. 3, from which a variation of over 10 dB SPL can be seen at around 600 Hz for the microphone locations at z=0 and z=0.8". In Figure 4, the differential SPLs spectra are plotted as a function of the sensor vertical positions at different frequencies. Large variations in SPL can be observed as the microphone's vertical location is changed from z=0 to z=0.9". In addition, as the microphone height is increased, the SPL does not increase or decrease consistently. Instead, the SPL fluctuates and the peaks and valleys can be observed at some discrete positions (e.g., z=0.575", z=0.6125", and z=0.85"), even at different frequencies.

The circumferential variation (or angular variation, θ, see Fig. 3) of the acoustic signatures from the microphone with respect to the fixed combustor was also examined from 0° to 90° in 10° intervals. The microphone was placed parallel to the combustor wall and was fixed at the vertical location of z=0.85". The combustor was set up on a rotational stage to allow any desired angular position change. As the relative tangential position between the combustor and the microphone was changed, we observed noticeable differences in the SPL spectra, i.e., the flame exhibited angular variations in the acoustic signatures. The maximum relative SPL variation observed over the 90° angular range was about 8 dB. The differential SPLs with respect to angular positions at different frequencies are illustrated in Figure 5. The variation of SPL obtained at different angular positions appears to be somewhat less than that obtained from changing vertical locations (Figure 4). This demonstrates that obtaining detailed information for understanding acoustic signatures generated from a combustion process requires incorporating multiple sensors that should be placed both axially along the combustor and circumferentially around the combustor with a defined degree of compactness. The extent of sensor compactness can be determined from the desired resolution, accuracy and other details required. Of course, a multi-sensor arrangement would be complex, more costly, and may even pose challenges in data processing. Our data has shown that simply using mean value of data from various locations (simulating array of sensor network) will be erroneous.

V. SENSOR NETWORKS CONSIDERATION IN PRACTICAL COMBUSTORS

It seems appropriate to conclude from the previous section that single sensors, at best, serve as process monitoring devices and are prone to substantial errors in determining the details of the ongoing process. Thus, as we begin to develop better, inexpensive and reliable sensors, one can envision that in the near future, very large-scale networks consisting of a large number of sensor nodes with a wide range of capabilities will be deployed for various applications, including combustors in advanced power plants. Although such sensor networks are expected to be a supporting technology for high performance and high efficiency combustors of the future, there are many challenges for deploying such sensor networks in combustors. First of all, one has to determine how one should develop an overall network architecture that can effectively accommodate the heterogeneity of a large number of sensors. Because having global control of all the sensors in the network is important, it is anticipated that a number of subsystems must be formed so that each subsystem is able to handle self-organization of complex adaptive systems with limited external direction. The underlying question is how these subsystems should be defined and how the sensors in each subsystem will interact with each other. A more difficult

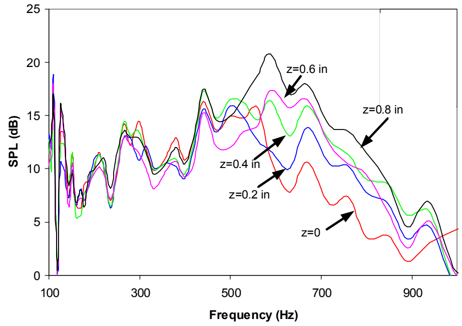

Figure 3. Spectra of differential SPL measured at different locations along the vertical axis (z).

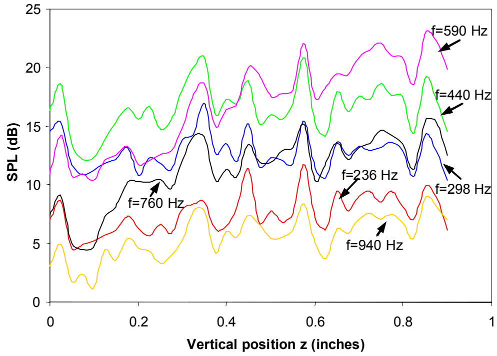

Figure 4. Differential SPL variation versus vertical locations at different frequencies.

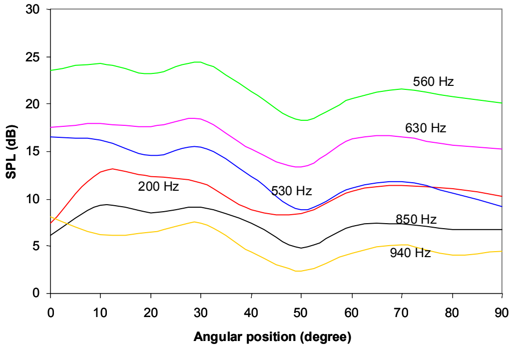

Figure 5. Differential SPL measured at different angular locations (for vertical position z = 0.85 inches)

problem relates to sensor coverage and placement. Along the same lines is the issue of determining a sufficient number of sensors and where these sensors should be placed to ensure a defined degree of convergence and confidence. In addition temporal reading of the network or parts of the network must be considered.

A. *Hierarchical network structure*

The sensors under consideration are heterogeneous in terms of various aspects including sensing, computing, and communicating. An integrated hierarchical framework is proposed here to accommodate such heterogeneity and render principles for the design and deployment of sensor networks, including the global control layer, the sensor leader layer, and the underlying heterogeneous sensor notes. In this framework, as illustrated in Figure 6, sensor notes are logically organized into different cells (clusters) according to the model-mimicking plant behavior. Each cell typically includes sensors that possess different capabilities and various computational capabilities. In fact, the first principle that is identified for deploying sensor networks is that, in general, all cells in a combustor should collaborate. This is a commonly agreed upon principle. Typically, a group of sensors residing in the same cell work together for some monitoring tasks and the data acquired from these sensors is delivered to the sensor leader in the cell. One model that will be considered in this study is the linking the data acquired by the sensors to a hierarchy of computational models. This creates a hybrid reporting system where each cell can extract more detailed information about the combustion process than could be obtained by the sensors alone.

After a set of sensors is selected as a cell, the second principle is identified as follows: the monitoring task should be tackled only by the sensors in the cell (to the maximum possible extent), and the solution should not assume dependency or seek outside help from sensors in other cells. This *independence* rule matches practical applications well and greatly simplifies the design problem. One cannot design and deploy sensor networks by considering all possible resources at all times.

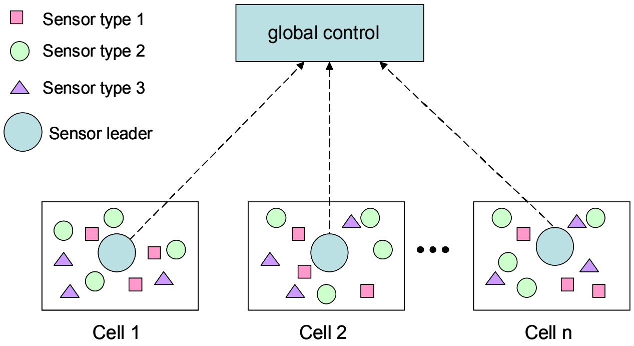

Figure 6. Schematic of hierarchical network structure.

Given the set of (possibly heterogeneous) sensors (e.g., measuring the concentration of different species in a combustion system), the next principle can be stated as follows: the problem should be solved by the sensors in a *distributed* manner with help from the integrated hierarchy of models that creates the computational object; no centralized algorithm should be dependent on other external parameters. To enable distributed computation, communication (and therefore coordination) between sensors in a cell is needed. Distributed algorithms inherently possess better scalability and security properties because they can provide efficient communication protocols and distributed algorithms to solve the incoming coverage determination and sensor placement problems. At the cell level, local sensing and control is organized by the sensor leader, which is essentially a processor with computational and communication capabilities. In the case of fiber optic sensors, a cell itself can be an independent sensor system with multiplexed sensors and a central processor. Each of these cells is then an independent self-identified object in which the output is created by independent coordination between the sensors and the hierarchy of models to respond to changing conditions and needs for information from the higher order collective of objects.

Upon finishing the self-organization, sensing, and control in each cell, the sensor leader can report the information to a global control station. The need for the global controller for power plant operation is unknown and understanding the mechanisms needed for the global control and the coordination algorithms that unite the system together is one of the primary long-range goals of this study. Currently, it appears that the complexity of the hybrid sensor/computational system, the number sensors and cells, and need for overall system integrity over a wide range of conditions will require the use of various computation intelligence and complexity management tools.

B. *Sensor coverage*

The coverage problem of sensor networks can be posed in different ways. One way would be to determine the achievable coverage level in an area where sensors have already been deployed. This is the classical *coverage determination* problem. On the other hand, one may ask how the sensors should be organized in a given area so that some coverage level can be guaranteed. This formulation is the coverage-constrained *sensor placement* or *deployment* problem. Sensor placement directly influences resource management and the type of back-end processing and exploitation that must be carried out with sensed data in distributed sensor networks.

In practical combustors, determination of the general sensor coverage problem needs to be tailored to include the characteristics of the combustor. Given a set of sensors deployed in a target area (the area of a cell), one needs to determine if the area is sufficiently covered, or *k-covered*, which represents that every point in the area is covered by at least *k* sensors (same types of sensors or heterogeneous sensors), where *k* is a predefined constant. Applications requiring $k > 1$ may occur in situations where stronger monitoring is necessary, such as locations with a large spatial or temporal gradient, as is encountered in some combustion devices. It can also occur when multiple sensors are required to detect an event. Enforcing $k \geq 2$ is also necessary for fault-tolerant purposes. A fundamental question is how many sensors are enough. This question should be addressed by using an available combustion model or hierarchy of models that can tell us the condition of each zone in the combustor. The principle focus here is that for certain critical locations, redundancy is necessary and thus $k > 1$ needs to be satisfied. Ideally, based on the combustion model prediction, the targeted coverage level of each cell in the combustor can be determined.

The second fundamental question to be addressed is how one can carry out effective sensor placement to realize the targeted coverage level. This is currently a somewhat more challenging issue to address. There have been several attempts to solve this problem with a graphic solution for some region with an ideal geometry. The solution can be easily translated to a distributed algorithm where each sensor only needs to collect local information to make its decision. Instead of determining the coverage of each location, our approach[14] tries to look at how the perimeter of each sensor's sensing range is covered, thus leading to an efficient polynomial time algorithm. As long as sensor perimeters are sufficiently covered, the whole area is sufficiently covered. A challenging problem of sensor coverage and placement in a three-dimensional area of a combustor will be explored.

VI. CONCLUDING REMARKS

The results presented here using a single sensor have shown that combustors posses significant spatial variation. A single sensor is inadequate to provide detailed information from the combustor, particularly when there are large-scale temporal and spatial variations. The peak signal, located downstream from the combustor, was found to depend on geometry and operational parameters. The results clearly identify the need for a multi-sensor network placed around the combustor for seeking detailed information that can allow for better control to achieve higher efficiency and performance. A preliminary sensor network framework for advanced combustion systems is presented. It aimed at providing a detailed database for model validation and model development for better decision making and intelligent combustor development,. Previous practices of one or two sensors from a combustor provide little to no, and sometimes even misleading, information on the ongoing combustion process in a system. The roles of various sensors are discussed. Sensor response at different locations of a combustor is presented. The manner in which a hierarchical sensor network can be realized is also presented.

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