# Combustion control using a multiplexed diode-laser sensor system

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## Abstract

A multiplexed diode-laser sensor system, comprised of two InGaAsP diode lasers and fiber-optic components, has been developed to non-intrusively measure temperature and species concentration over a single path for closed-loop process control using laser absorption spectroscopy techniques. The system was applied to measure and control the gas temperature in the post-flame gases along a 7-cm long path 6 mm above the surface of a Hencken burner (multiple $CH_4$-air diffusion flames). The wavelengths of the lasers were independently current-tuned across $H_2O$ transitions near 1343 nm ($\nu_1+\nu_3$ band) and 1392 nm ($2\nu_1$, $\nu_1+\nu_3$ bands). Temperature was determined from the ratio of measured peak absorbances. $H_2O$ concentration was determined from the measured peak absorbance of one transition at the measured temperature. The temperatures recorded using the sensor compared well with those measured by thermocouples. A computer-controlled closed-loop feedback circuit that actuated the fuel flow in response to the difference between the measured and desired gas temperature was used to control the temperature in the probed region. The sensor system was also used to measure the frequency of temperature fluctuations above the flame. The results demonstrate the potential of multiplexed diode lasers for rapid, continuous, *in situ* measurements and control of important parameters in combustion environments.

## Introduction

Non-intrusive measurements of multiple flowfield parameters have been demonstrated in a variety of flowfields using diode-laser absorption diagnostics.[1-3] Recently, the outputs of three, independently operated diode lasers have been multiplexed into a single path using fiber-optic components to probe multiple absorption transitions of $H_2O$ and $O_2$, or $H_2O$ and $CH_4$, simultaneously.[4,5] These multi-species sensor systems are capable of measuring temperature, pressure, and species concentrations at kHz rates along several paths simultaneously by using appropriate fiber splitters without increasing the number of laser sources.[4] In the present investigation, a closed-loop combustion-control system which combines a multiplexed diode-laser sensor with a computer-controlled feedback system is demonstrated to measure and control the gas temperature and $H_2O$ mole fraction in the burned gases above a $CH_4$-air flame.

## Theory

The theoretical basis for determining gas temperature and species concentration from measured absorption spectra recorded in combustion flows and the spectroscopic parameters of the $H_2O$ transitions probed[6,7] have been described previously.[1-5] In brief, the gas temperature was determined from the ratio of measured $H_2O$ absorbances obtained by tuning the wavelength of the narrow-bandwidth diode lasers across transitions near 1343 nm ($\nu_1+\nu_3$ band) and 1392 nm ($2\nu_1$, $\nu_1+\nu_3$ bands). $H_2O$ mole fraction (or concentration) was determined from the measured absorbance at a particular wavelength using the known absorption line strength at the measured temperature.

## Experimental Method

Figure 1 shows the general arrangement of the combustion-control experiment. The details of the

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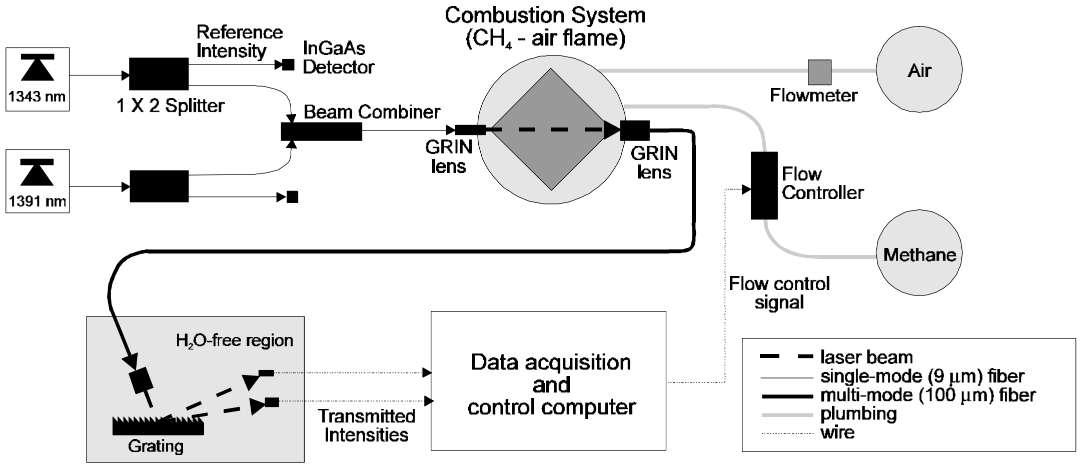


**Fig. 1** Schematic diagram of the combustion-control experimental arrangement.

laser system and the operating conditions employed to control the lasers have been previously specified.[4,5] The system includes two distributed feedback (InGaAsP) diode lasers wavelength tuned at a 2-kHz repetition rate over the selected transitions by ramp-modulating the individual injection currents to yield single-sweep spectrally-resolved absorption records every $10^{-3}$ sec. The individual laser outputs were combined into a single path using single-mode fiber splitters and couplers. The multi-wavelength beam was directed through the flowfield using a gradient index of refraction (GRIN) lens fused to the end of the (9 µm) fiber. The transmitted beam was coupled into a multi-mode (100 µm) fiber with a 7-mm diameter fused GRIN lens. The larger diameter receiving lens and optical fiber were used to maximize coupling efficiency and minimize effects of beam deflection caused by density gradients in the probed region. The transmitted multi-wavelength light was de-multiplexed (spectrally separated) into the constituent laser wavelengths by directing the beam at a non-normal incidence angle onto a diffraction grating (600 grooves/mm, blazed at 1 µm). The beams were diffracted at angles that corresponded to each wavelength and subsequently monitored with InGaAs photodiodes (200-kHz bandwidth). The detector voltages were digitized by a 1 MHz, 12-bit, 2-channel D/A board (scopecard) resident in a personal computer.

The system was used to record $H_2O$ absorption spectra through the product gases of a $CH_4$-air diffusion flame generated by a Hencken burner. The burner, shown schematically in figure 2, consists of a 2-inch (on a side) square array of diffusion flamelets sustained by a matrix of 0.5-mm internal diameter, 16.7-mm long stainless steel needle tubes that carry fuel ($CH_4$, in this case) from a reservoir fed by a circular annulus. At the top of the burner, the fuel exits the tubes and mixes with streams of co-flowing air to yield ≈460 diffusion flamelets. For the typical operating conditions ($CH_4$ flow rate 4.5-5.3 *l*/min, $CH_4$ velocity 45-53 cm/s in the tubes; air flow rate ≈50 *l*/min, air velocity in the flow straightener ≈120 cm/s), the flow was laminar ($Re_D < 100$) and the tips of the flamelets were less than 3 mm above the burner surface.

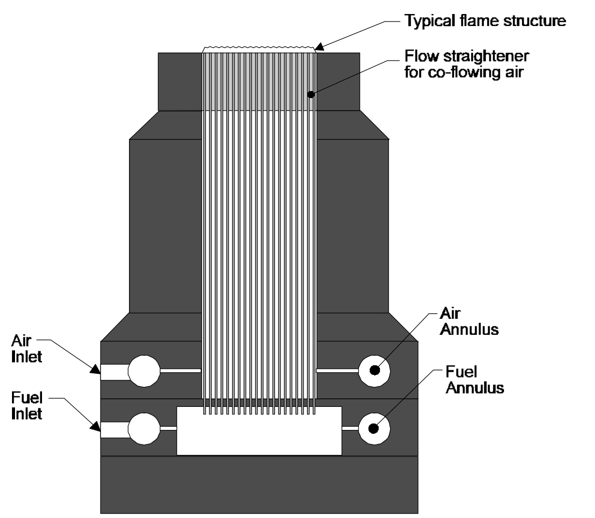


**Fig. 2** Schematic diagram of the Hencken burner used to sustain a $CH_4$-air flame.

The flame temperature was varied by adjusting the fuel flow rate, and thus the equivalence ratio, using a proportional, direct-acting, voltage-controlled, solenoid valve and maintaining a constant air flow rate. Figure 3 plots the gas temperature 6 mm above the burner surface measured with a type-S thermocouple (bare, platinum-platinum/10% rhodium, 5-mil), corrected for radiation effects, as a function of the flow controller input voltage. For the given air flow rate, the flow-controller voltage variation of 2.61 V - 2.81 V yielded an almost linear variation in temperature over the range 1810 K - 2200 K, demonstrating the ability to control the gas temperature by changing the $CH_4$ flow rate. The inverse slope of the temperature variation with controller voltage, 0.5 mV/K, was used as the proportional gain factor (G) for the feedback control system.

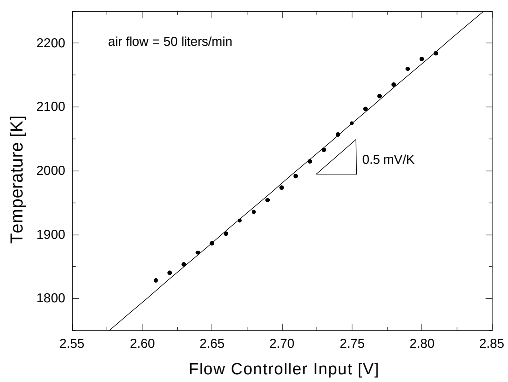


**Fig. 3** Gas temperature values as a function of methane flow controller voltage (and thus flow rate) along a path 6 mm above the burner surface measured with a type-S thermocouple (corrected for radiation effects) for a constant air flow rate. The inverse slope of the variation of temperature with controller voltage was used as the proportional gain factor for the feedback control system.

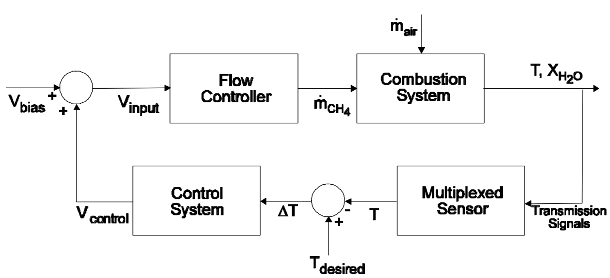


**Fig. 4** Block diagram illustrating the strategy used for closed-loop control of the gas temperature.

Figure 4 illustrates the strategy for closed-loop control of the gas temperature in the probed region. The initial operating conditions in the burner ($T_{initial} \approx$ 2050 K) were established by supplying a 2.74-V bias to the fuel flow controller which yielded a $CH_4$ flow rate of ≈4 *l*/min and maintaining the air flow rate near 50 *l*/min. A flow controller voltage of 2.79 V corresponds to an equivalence ratio = 1. The error signal for the control algorithm was proportional to the difference between the temperature determined from peak absorbances and the desired set point ($T_{desired}$). The feedback control voltage signal ($V_{control}$), the product of the temperature difference ($T-T_{desired}$) and the gain factor G, was added to the bias voltage of the flow controller to effectively adjust the gas temperature to the desired value.

## Data Analysis

A computer program, written in C, was used for data analysis, signal processing, and to determine the feedback signal to the actuator. Figure 5 presents typical raw data (single-sweep) transmission signals obtained simultaneously by tuning the lasers independently at a 1-kHz rate across the selected $H_2O$ absorption features over a 7-cm long path 6 mm above the flame. Peak absorbance was determined from (the maximum value of) the negative logarithm of the normalized transmittance.[3] The gas temperature (T) was determined from the ratio of the peak absorbances.[2-5]

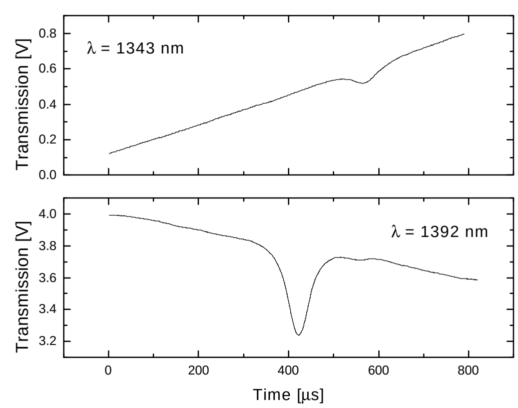


**Fig. 5** Typical raw data (single-sweep) transmission signals obtained simultaneously by tuning two diode lasers independently at a 1-kHz rate across $H_2O$ absorption features near 1343 nm (top frame) and 1392 nm (bottom frame) in the burned region 6 mm above a $CH_4$-air flame.

## Time response of sensor system

To demonstrate the ability of the multiplexed sensor to record rapid temperature measurements, the gas temperature above the flame was rapidly increased by supplying a voltage step (0.16 V) to the $CH_4$ flow controller to increase the equivalence ratio towards stoichiometric. Figure 6 illustrates the resulting temperature variation in the post-flame gases 6 mm above the burner measured using the multiplexed sensor and two different thermocouples (3 mil, 5 mil) corrected for radiation effects. The measurements are in excellent agreement prior to the applied step (for temperatures near 1825 K). After the step, the temperatures recorded by the multiplexed sensor (at a rate of 1 measurement every 2 ms) rise to within 37% of the final steady-state value of ≈2150 K in ≈18 ms. The oscillatory overshoot has a significant 12-Hz component that may be due a natural instability of the flame excited by the step change in the fuel flow rate. The response time of the burner is due predominantly to the finite flow-controller response and the gas residence time in the volume from the flow controller to the probed region.

The measured thermocouple rise times were 70 ms (3 mil) and 120 ms (5 mil). The calculated theoretical response times for the thermocouples (modeled as perfectly-conducting, non-radiating spheres) were ≈45 ms (3 mil) and ≈116 ms (5 mil).

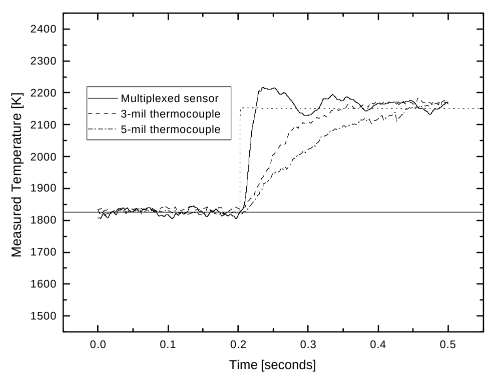


**Fig. 6** Comparison of temperatures measured in the burned region above a $CH_4$-air flame due to an applied step change in the fuel flow rate using the multiplexed sensor and type-S thermocouples.

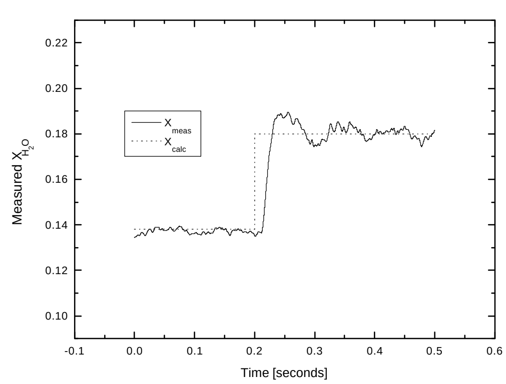


**Fig. 7** Comparison of $H_2O$ mole fractions ($X_{meas}$) determined (simultaneously with temperature values) from peak absorbance measurements (dots) using the multiplexed sensor with calculated chemical-equilibrium values ($X_{calc}$) for the conditions described in figure 6.

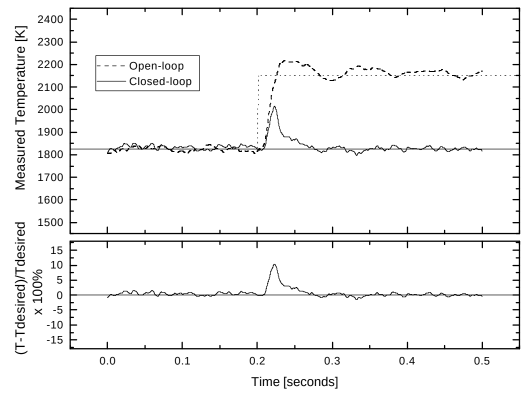


**Fig. 8** Measured temperatures in the burned region above the $CH_4$-air flame illustrating the capability of the closed-loop control system to maintain the desired set point temperature by compensating for a perturbation in the fuel flow rate. The top frame shows the closed-loop performance with a typical open-loop (no feedback) response included for comparison. The bottom frame plots the percentage temperature variations between the measured values and the desired value of 1825 K.

Figure 7 compares values of $H_2O$ mole fraction determined from gas temperature and peak absorbance measurements using the multiplexed sensor ($X_{meas}$) with estimated chemical equilibrium values ($X_{calc}$) calculated at the steady-state temperatures for the burner operating conditions described in Figure 6. Adiabatic flame calculations suggest $X_{calc}$ = 0.173. The calculations illustrated in Figure 7 assume a moderate 3% heat loss, due to heat transfer to the uncooled burner, and yield $X_{calc}$ = 0.18. The fluctuations in the $X_{meas}$ values (≈9-10%) are primarily due to the uncertainty and fluctuations in the $CH_4$ flow rate through the solenoid valve (5%) and temperature fluctuations in the flowfield (4-5%). Thus, for relatively temperature-insensitive systems, measurements of species mole fraction (or concentration) could be used as a sensed parameter in a closed-loop feedback system for process control.

Figure 8 demonstrates the capability of the closed-loop control system to respond to a step change in fuel flow rate. The system measures a temperature and computes an appropriate control signal every 2 ms to rapidly identify and suppress measured variations from the desired set point value. The top frame illustrates both the closed-loop performance (solid) of the control system and the open-loop response (dash) of the burner to the applied change in fuel flow rate.

The bottom frame plots the percent deviation from the desired temperature (1825 K). The maximum variation between the measured temperature and the desired value, which occurred immediately after the step change in the fuel flow rate, was 10%. The standard deviation in the percentage temperature variation was less than 1% for the total measurement interval.

The 1/e response time of the closed-loop control system, the time necessary for the mean measured gas temperature to reach a value within 37 % of the relative temperature differential $(T-T_{desired})/T_{desired}$ due to the applied step, was ≈10 ms. The settling time, the time necessary for the relative temperature differential to decrease below 3% after the step, was ≈30 ms.

The response time of the system can be reduced by using an improved data transfer procedure to the computer, reducing the scan time of the laser, using a fixed-frequency absorption measurement strategy,[3] or, most importantly, minimizing the gas volume (and thus transit time of the gas) from the flow controller to the burner surface. In addition, other actuation strategies may be applied to reduce the phase lag between the control signal to the actuator and the resultant gas temperature change (e.g., acoustic pressure variations applied directly to the flowfield).

## Frequency measurements of temperature fluctuations

In addition to recording time-dependent temperature and $H_2O$ concentration measurements, the sensor system was used to determine the frequency of temperature fluctuations in the flame. Rapid frequency measurements of temperature fluctuations can be used to monitor applied and parasitic frequencies in driven systems to enable the timely determination and control of unwanted instabilities. In particular, secondary oscillation modes could be measured and to determine a shift from a stable to an unstable mode during a process such as fuel scheduling in a large-scale system with multiple acoustic modes.

Typically, measurements of temperature fluctuations in high-temperature flows are limited by thermocouple response times. The computer-controlled multiplexed diode-laser sensor system, on the other hand, yields a temperature measurement every 2 ms. The (fast) Fourier transform (FFT) of a time-dependent temperature trace may be used to determine the power spectra (the squared magnitude of the FFT) to yield information about the frequency of temperature fluctuations.

To demonstrate the technique, a sinusoidal modulation voltage was applied to the fuel flow controller to yield an oscillating flow rate and a fluctuating temperature field at a known frequency in the probe region. The fluctuations were monitored using the multiplexed sensor. The frequency of the dominant oscillatory mode was determined from the power spectrum after an appropriate number of temperature measurements. For the present work, 64 measurements recorded in a total measurement time of 128 ms were used to determine the dominant fluctuation frequency with a Nyquist-limited resolution of ±4 Hz.

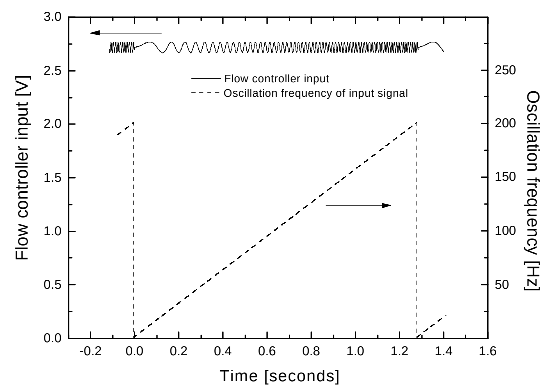


**Fig. 9** Frequency-modulated voltage waveform (bias signal = 2.72 V, sinusoidal modulation signal = 0.1 Vpp) applied to the flow controller (left axis) and the resulting oscillation frequency (right axis) which increases linearly from 1 Hz to 201 Hz at a rate of 160 Hz/sec.

The voltage waveform with a linearly varying frequency (Figure 9) was applied to the flow controller to demonstrate the ability of the sensor system to record measurements in flowfields with changing fluctuation frequencies. The input voltage to the controller (top part of frame) and oscillation frequency (bottom part of frame) as a function of time are plotted using the left and right axes, respectively. As a result of the finite measurement time (128 ms for 64 temperature measurements), the measured fluctuation frequency (in the probed dynamic flow) has an uncertainty given by the product of the rate of change of the applied modulation frequency and the measurement interval.

Figure 10 shows an example data set used to determine the dominant fluctuation frequency in the flowfield. The inset shows the measured time-dependent temperature values and the graph plots the resultant power spectrum. The total width (FWHM) of the spectrum (≈20 Hz) is due to the frequency variation (160 Hz/sec) within the measurement interval (128 ms) and is small relative to the total range of frequencies encountered during the applied waveform used in this example.

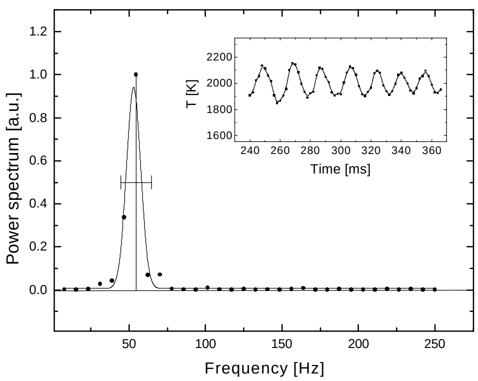


**Fig. 10** Power spectrum determined from 64 temperature measurements recorded in a 128-ms interval (shown in the inset). The error bar reflects the broadening due to the 20 Hz change in frequency that occurred during the 2-ms measurement interval.

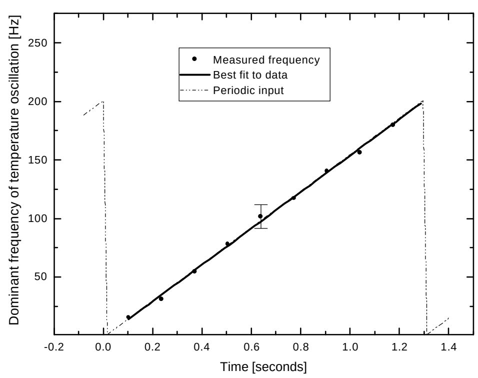


**Fig. 11** Measurements of the dominant temperature oscillation frequency in the $CH_4$-air flame due to a periodic frequency-modulated voltage waveform applied to the fuel flow controller. Each data point represents the average dominant oscillation frequency in a 128-ms interval. The error bar reflects the systematic variation in the modulation frequency during the measurement interval.

Figure 11 illustrates measurements of fluctuation frequencies in the flow as the applied sinusoidal voltage waveforms vary linearly from 1 Hz to 200 Hz at a rate of 160 Hz/sec over a 1.2 sec interval. The excellent agreement between the measured and expected values suggests that the technique is reliable and may be extended to other time-varying and more complex and realistic flowfields that contain a superposition of frequencies.

## Conclusions

A closed-loop feedback system which incorporated a multiplexed diode-laser sensor was used to monitor and control the gas temperature along a single path in the burned gases above a $CH_4$-air flame. Gas temperature was determined from the ratio of measured $H_2O$ absorbances recorded by tuning two diode lasers independently across selected transitions near 1343 nm and 1392 nm. $H_2O$ mole fraction was determined from measured absorbance and gas temperature values.

The system minimized the difference between the measured gas temperature and a desired value by actively controlling the methane flow rate to the burner using a voltage-controlled solenoid valve. The system was capable of controlling the gas temperature to within 1% (standard deviation) of the desired value in the range 1825 K - 2150 K. The frequency response of the control system, limited primarily by the gas residence time in the burner, may be improved by reducing the burner reservoir volume, by increasing the digital transfer rate to the computer, and by using fixed-frequency absorption measurements to decrease the measurement time.

The computer-controlled sensor system was applied for on-line determination of the frequencies of temperature fluctuations in the flowfield from the calculated Fourier transforms of the time-dependent temperature measurements. Rapid frequency measurements of temperature oscillations is a diagnostic which can be used in a control strategy to minimize the effects of unwanted operational modes and to maximize the performance in passive and actively driven combustors, turbines, and incinerators.

Multiplexed diode-laser sensing holds promise for improved monitoring and control of combustion and other high-temperature process streams, particularly for applications that require remote and non-intrusive monitoring.

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