Scanned- and Fixed-Wavelength Absorption Diagnostics for Combustion Measurements Using Multiplexed Diode Lasers

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A multiplexed diode-laser sensor system comprising two diode lasers and fiber-optic components has been developed to nonintrusively monitor temperature and species mole fraction over a single path using both scanned- and fixed-wavelength laser absorption spectroscopy techniques. In the scanned-wavelength method, two InGaAsP lasers were current tuned at a 2-kHz rate across H_2O transitions near 1343 nm and 1392 nm in the $2\nu_1$ and $\nu_1 + \nu_3$ bands. Gas temperature was determined from the ratio of single-sweep integrated line intensities. Species mole fraction was determined from the measured line intensity and the calculated line strength at the measured temperature. In the fixed-wavelength method, the wavelength of each laser was fixed near the peak of each absorption feature using a computer-controlled laser line-locking scheme. Rapid measurements of gas temperature were obtained from the determination of peak line-intensity ratios. The system was applied to measure temperature and species concentration in the postflame gases of an H_2-O_2 flame. The good agreement between the laser-based measurements obtained using scanned- and fixed-wavelength methods with those recorded with thermocouples demonstrates the flexibility and utility of the multiplexed diode-laser sensor system and the potential for rapid, continuous measurements of gasdynamic parameters in high-speed or transient flows with difficult optical access.

Introduction

RAPID measurements of gasdynamic properties have been demonstrated in a variety of flowfields using scanned-wavelength, diode-laser absorption diagnostics.[1-3] Diode-laser absorption techniques have been used to determine the water-vapor concentrations and gas temperatures in shock-heated flows and, thus, to validate theoretical models of hypersonic combustion processes. Recently, a multiplexed diode-laser sensor system was developed to extend these single-species laser-absorption diagnostics by simultaneously probing multiple H_2O and O_2 transitions along a single path using three independently tuned, narrow-linewidth diode lasers and fiber-optic components. This multispecies sensor system is capable of measuring temperature, pressure, and species concentrations at a rate limited by the ability of a diode laser to scan across an absorption feature (typically about 10 kHz).[4] By combining the outputs of several lasers into a common path using optical fibers, the capability of the diode-laser sensor system for line-of-sight measurements is significantly enhanced. Furthermore, multispecies measurements along several paths may be easily realized without increasing the number of laser sources by using appropriate fiber splitters.

The present effort extends the capabilities of our initial multiplexed diode-laser sensor system in two ways. First, the system is applied to measure the temperatures present in a combustion flowfield produced by an H_2-O_2 flame sustained above a flat-flame burner using scanned-wavelength absorption spectroscopy.

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Second, a fixed-wavelength absorption strategy is developed using a computer-controlled line-locking scheme to enable rapid temperature measurements at a rate limited by the frequency response of the data acquisition system (which typically includes amplified photodetectors, associated electronics, and A/D converters) and not by the laser tuning rate.

Laser-absorption diagnostics are often constrained by the finite continuous tuning range of the probe laser (typically ≤ 2 cm^{-1} for diode lasers). This limits the selection of temperature-sensitive lines that may be probed in a single scan. The multiplexed diode-laser sensor system overcomes this limitation by combining the output beams of multiple lasers, each operating in a different spectral region, into a single path and, thus, allows us to probe the optimum (e.g., temperature-sensitive) absorption transitions without reducing spatial resolution. In addition, the system allows all diode lasers to operate independently and all flowfield and étalon transmission intensities to be monitored using individual photodetectors and, thus, recorded on separate voltage channels. This simplifies the data reduction procedure and increases the data acquisition rate significantly compared with (time-division multiplexing) methods that combine different beams into a single fiber and temporally stagger the tuning of the individual lasers to discriminate the constituent spectral channels.[2]

Theory

The transmission of narrow-linewidth radiation at frequency v through a uniform medium of length L (cm) may be described by the Beer–Lambert relation,

$$T_v \equiv I_v/I_0 = \exp(-k_v L) \tag{1}$$

where T_v is the spectral transmittance of the medium and I_v is the spectral intensity at L. Also I_0 is the incident intensity and k_v is the spectral absorption coefficient (cm^{-1}). The spectral absorption coefficient near a spectral line may be expressed as

$$k_v = S_{lu}(T) X_{abs} P \phi_v \tag{2}$$

where $S_{lu}(T)$ (cm^{-2} atm^{-1}) is the temperature-dependent transition line strength, X_{abs} is the mole fraction of the absorbing species, P is

Table 1   H₂O¹⁶ spectroscopic parameters, T = 296 K

Line	λ, nm	ν, cm^{-1}	S, cm^{-2} atm^{-1}	E'', cm^{-1}	J'	k'_a	k'_c	J''	k''_a	k''_c
1ᵃ	1391.712	7185.394	1.08E-03	447.252	5	2	3	6	1	6
1ᵃ	1391.711	7185.399	2.60E-04	1474.981	9	5	4	9	5	5
1ᵇ	1391.703	7185.442	1.04E-04	782.41	8	0	8	7	2	5
1ᵃ	1391.677	7185.577	3.00E-04	446.511	6	1	6	5	2	3
1ᵇ	1391.673	7185.597	1.88E-02	1045.058	6	6	0	6	6	1
1ᵃ	1391.624	7185.847	2.00E-05	742.073	6	4	2	5	5	1
2ᵇ	1343.300	7444.351	4.00E-04	1774.752	13	2	12	12	2	11
2ᵇ	1343.297	7444.369	5.90E-04	1806.672	14	0	14	13	1	3
2ᵇ	1343.297	7444.561	1.37E-04	1774.619	13	1	12	12	11	1
2ᵇ	1343.297	7444.695	4.58E-04	1437.969	11	2	9	10	2	8

ᵃ$2\nu_1$ band.   ᵇ$\nu_1 + \nu_3$ band.

the total pressure, and ϕ_ν (cm) is the frequency-dependent line shape function normalized such that $\int \phi_\nu \, d\nu \equiv 1$. The line strength S_{lu} is proportional to the number density of absorbers (per unit pressure) through[5]

$$S_{lu}(T) = N_L \left(\frac{273}{T}\right) \left(\frac{\pi e^2}{m_e c^2}\right) F_B(T) f \frac{S_{j''j'}}{2J''+1} \qquad (3)$$

where N_L (cm^{-3}) is Loschmidt's number, $T(K)$ is the temperature, e (esu) and $m_e(g)$ are the electron charge and mass, c (cm/s) is the speed of light, $F_B(T)$ is the Boltzmann fraction in the absorbing state, f is the oscillator strength for a given rovibronic band, and $S_{j''j'}$ is the normalized Hönl–London factor. Spectral line parameters, including line strengths and positions, for water vapor at 296 K have recently been measured accurately.[6] The ratio of two spectral absorption coefficients at the frequency for maximum absorption R_{peak} may be expressed as

$$
\begin{aligned}
R_{\text{peak}} &\equiv k_{\nu,1}/k_{\nu,2} \\
&= \frac{S_{lu,1}(T_0)\phi_{\nu,1}}{S_{lu,2}(T_0)\phi_{\nu,2}} \exp\left[-\frac{hc}{k}\left(E''_1 - E''_2\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]
\end{aligned}
$$

$$(4)$$

where $k_{\nu,i}$ and $S_{lu,i}(T_0)$ are the spectral absorption coefficient and the line strength for transition i at temperature T_0, respectively; E''_i is the corresponding lower state energy level; and h and k represent Planck's and Boltzmann's constant, respectively. If the probed absorption features (denoted 1 and 2) consist of multiple transitions, Eq. (4) may be generalized to include the contributions from all line shapes to the total absorption

$$
\begin{aligned}
R_{\text{peak}} &= \sum_i k_{\nu,i} \Big/ \sum_j k_{\nu,j} = \left\{ \sum_i S_{lu,i}(T_0)\phi_{\nu,i}(T, 2\gamma) \right. \\
&\times \left. \exp\left[-\frac{hc}{k}E''_i\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]\right\} \Big/ \left\{ \sum_j S_{lu,j}(T_0)\phi_{\nu,j}(T, 2\gamma)\right. \\
&\times \left. \exp\left[-\frac{hc}{k}E''_j\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]\right\}
\end{aligned}
$$

$$(5)$$

where the indices i and j denote the individual transitions within absorption features 1 and 2, respectively, and the implicit dependence of ϕ on gas temperature and collision width 2γ has been denoted. Note that Eqs. (4) and (5) are expressed relative to the reference state E''. Integrating k_ν [Eq. (2)] over an entire line shape yields an expression for the line intensity K given by

$$K = \int_{-\infty}^{\infty} k_\nu \, d\nu = S_{lu}(T) X_{\text{abs}} P \qquad (6)$$

Thus, the mole fraction of a given species may be determined from the measured line intensity and Eq. (6) if the temperature, total pressure, and line strength are specified. The ratio of integrated line
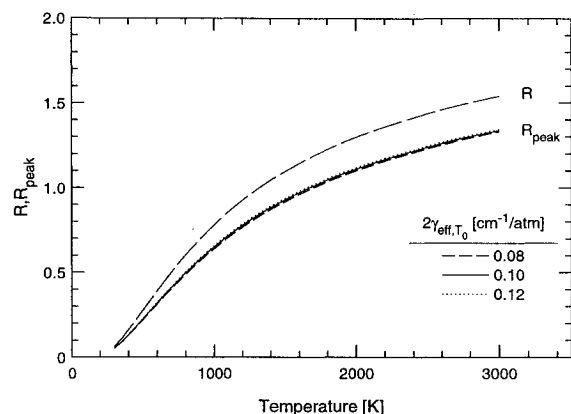

Fig. 1   Temperature dependence of the integrated line intensity ratio R and the peak absorption ratio R_{peak} for various values of 2γ.

intensities R yields an expression independent of line shape and solely a function of temperature,

$$
\begin{aligned}
R &\equiv \int \left(\sum_i k_{\nu,i}\right) d\nu \Big/ \int \left(\sum_j k_{\nu,j}\right) d\nu = \left\{ \sum_i S_{lu,i}(T_0)\right. \\
&\times \left. \exp\left[-\frac{hc}{k}E''_i\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]\right\} \Big/ \left\{ \sum_j S_{lu,j}(T_0)\right. \\
&\times \left. \exp\left[-\frac{hc}{k}E''_j\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]\right\}
\end{aligned}
$$

$$(7)$$

Table 1 lists the spectroscopic parameters of the probed H₂O transitions. For simplicity, both probed absorption features, which consist of overlapping line shapes, are referred to as lines. Figure 1 illustrates the variation of R and R_{peak} with temperature for typical values of the effective Lorentzian broadening parameter $2\gamma_{\text{eff}}$ for flowfields containing both water and argon. The insensitivity of both R and R_{peak} to collisional broadening effects indicates that Eqs. (4) and (5) are relatively insensitive to the mole fractions of the constituent species in the probed flowfield. As a result, an accurate measurement of either the ratio of integrated or peak line intensities may be used to determine temperature using Eq. (5) or Eq. (7), respectively, without a precise value of the effective broadening parameter. For example, a 25% variation of $2\gamma_{\text{eff}}$ yields a variation in the temperature of about 15 K at 1000 K (1.5%) and 35 K at 2000 K (1.8%).

Experimental Method

Figure 2 is a schematic diagram of the multiplexed diode-laser sensor system for the scanned-wavelength scheme. Details of the system have been described previously.[4] Table 2 lists the operating conditions employed to control the lasers. The system includes two independently operated diode lasers that, in the scanned-wavelength scheme, were tuned at a 2-kHz repetition rate over the desired transitions by ramp modulating the individual injection currents and, thus, yielding single-sweep measurements every 500 μs. In the present

Table 2   Operating conditions for the lasers

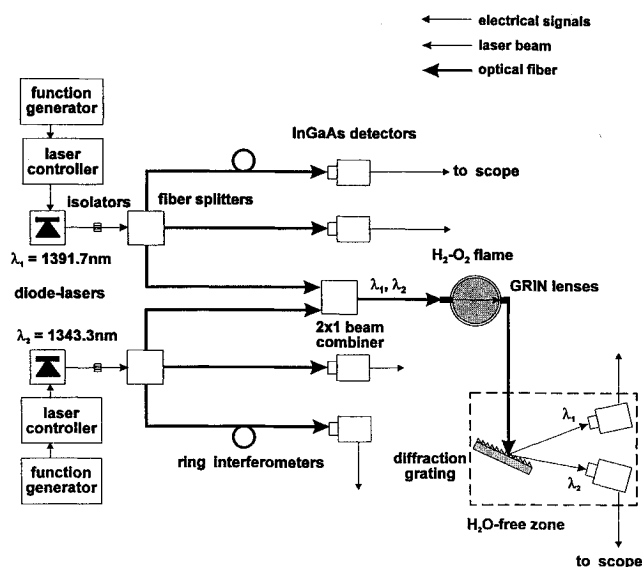| Laser	λ, nm	Case temperature, °C	Bias current, mA	Current modulation amplitude, mA
1	1391.7	24.5	157	45
2	1343.3	−9.5	62	26

Fig. 2   Experimental schematic of the multiplexed diode-laser sensor system used for scanned-wavelength absorption measurements.
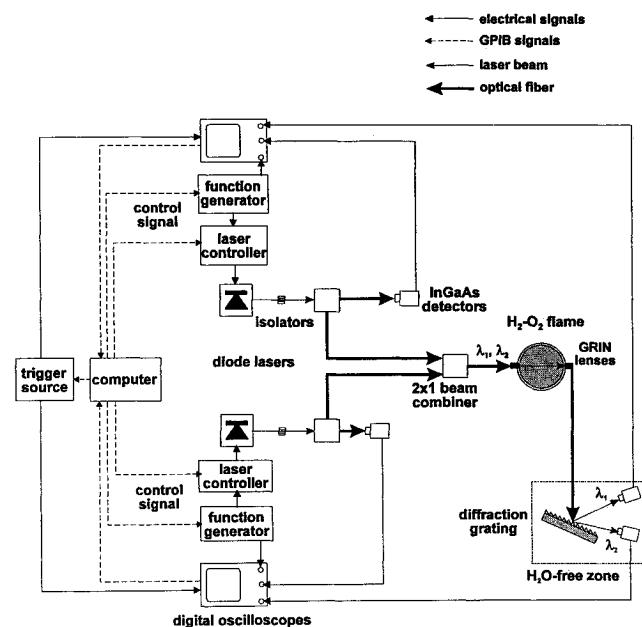

Fig. 3   Experimental schematic of the multiplexed diode-laser sensor system using a computer-controlled line-locking scheme for fixed-wavelength absorption measurements.

system, the beam width through the probed region was approximately 2 mm.

For the fixed-wavelength strategy, illustrated schematically in Fig. 3, each laser wavelength was maintained near the peak absorption value with a computer-controlled feedback system developed using LabVIEW® (National Instruments). Each laser wavelength was modulated over a 2.5-GHz spectral interval around the peak of each absorption feature by adding a 100-Hz current waveform to the dc bias of each laser. The analog voltage signals derived from the transmission and reference beams were converted to digital values using HP503A® (1024-point memory) and HP510® (512-point

memory) digital oscilloscopes with 8-bit vertical resolution and sent to a personal computer. The computer calculated the time-dependent product of absorption coefficient and path length using Eq. (1), searched for the respective maxima and the corresponding injection current values, and then sent the appropriate feedback currents necessary to maintain the wavelengths near the peak absorption values to the dc bias of each laser via general purpose interface bus. Since the system uses the measured transmission signal recorded in the flowfield as a control variable, it automatically compensates for shifts in the peak absorption due to temperature effects.

Transmitted and reference signals were recorded at a 1-MHz sampling rate whenever the wavelengths of both lasers were simultaneously within 50 MHz of each absorption peak, thereby allowing measurements every 1 μs. The laser wavelengths remained relatively constant and within 50 MHz of the respective line centers after the appropriate dc bias currents were determined. For both the fixed- and scanned-wavelength methods, the voltage signals were recorded continuously until the memories of both oscilloscopes were filled and then transferred to the computer for analysis. Thus, for the fixed-wavelength technique, when the laser wavelengths are close to line center, the measurement acquisition rate is limited primarily by the effective frequency response of the entire detection system which includes the (amplified) photodetector and the data recording (A/D conversion) electronics. For the scanned-wavelength technique, the measurement acquisition rate is limited essentially by the tuning rate of the lasers. The conversion from time to spectral frequency in the transmission and reference signals is performed during the data collection process using information contained within the appropriate interferometer (étalon) transmission traces.

The system was used to record absorption measurements through the product gases of a laminar, premixed H_2–O_2 flame sustained on a commercially available flat-flame burner (McKenna Products). The gas mixture exited the burner through a 1-cm-thick, 6-cm-diam cylindrical plug of sintered bronze that acted as a flame holder for the flat-flame sheet established immediately above the outer surface. The flame holder was continuously cooled by flowing about 12 l/min of water through copper tubing embedded within the porous metal. At this flow rate, the water temperature rose less than 15 K during passage through the burner. A separate porous metal ring fed by an independent gas plenum surrounded the primary plug and provided a shroud flow of N_2 gas. The shroud helped to flatten the horizontal flame sheet by stabilizing its outer edges, minimized the entrainment of ambient humid air into the postflame gases near the burner surface, and improved the uniformity of the temperature observed across the burner diameter. In addition, the N_2 gas effectively cooled the fiber-coupled gradient refractive index lenses that were located near the center of the annular shroud flow and used to direct and receive the multiwavelength probe beam through the flame.

Gas temperatures were determined by traversing an uncoated, 3-mil-diam bead-size type S thermocouple at the probed height (6 mm) above the burner surface. Time-averaged point-to-point variations in temperature were typically less than 1% of the nominal burner-center value except near the edges of the porous plug where the temperature decreased from the plateau of nominally 1100–1880 K to near ambient levels in approximately 4 mm. Gas temperature at a given height was controlled by varying the relative proportion of reactants (H_2, O_2) and diluent (Ar). Postflame temperatures were much lower than those calculated under adiabatic conditions due to significant heat transfer rates to the water-cooled burner surface.

Data Analysis

Figure 4 shows single-sweep transmission signals that were obtained simultaneously by tuning two lasers independently at a 2-kHz rate across H_2O absorption features over a 12-cm-long path through the H_2–O_2 flame using a double-pass configuration. Each time-dependent transmission signal was normalized by the incident laser intensity and transformed to a frequency-dependent line shape using information contained in the appropriate ring-interferometer transmission trace.

Figure 5 shows reduced single-sweep H_2O absorption line shapes recorded from the signals shown in Fig. 4. Measured profiles for lines 1 and 2 were least-squares fit to six and four overlapping Voigt
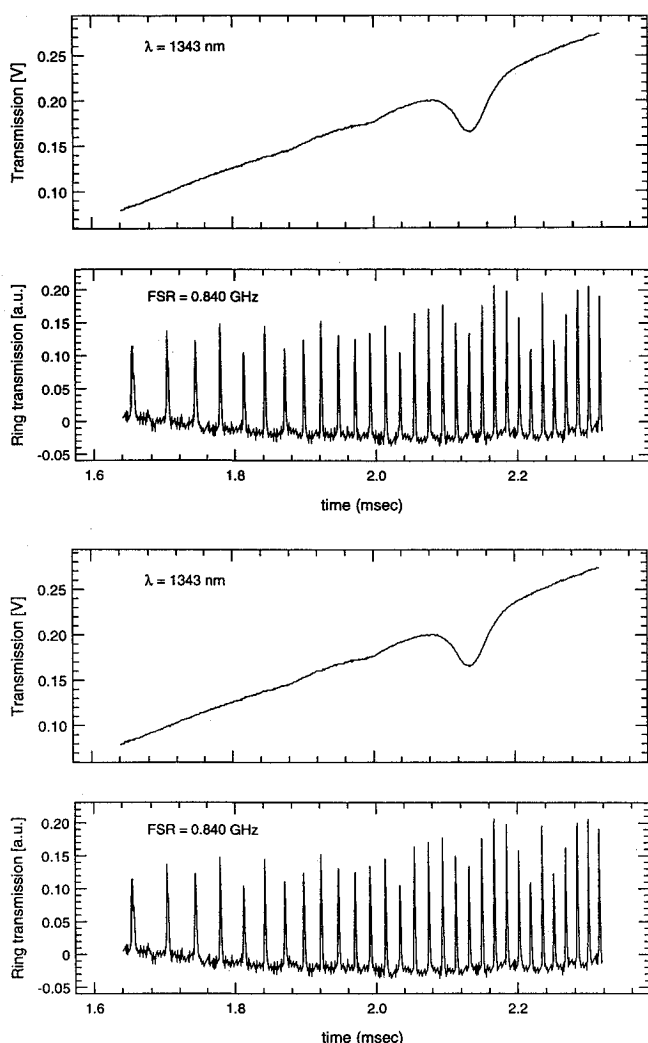
Fig. 4 Single-sweep transmission signals obtained simultaneously by tuning two diode lasers independently at a 2-kHz rate across H₂O absorption features over a 12-cm-long path through the product gases of an H₂–O₂ flame.

Fig. 5 Reduced single-sweep H₂O absorption line shapes near (top) 1343 nm and (bottom) 1392 nm recorded in a stoichiometric H₂–O₂ flame; the residual is the difference between the data and the multiline best-fit Voigt profile (solid line) determined from the superposition of the probed line shapes; the contributions (broken line) from the individual transitions also shown.

line shapes, respectively, using the tabulated intensity ratios and frequency separations.[6] A gas temperature value was determined by solving Eq. (5). The abscissas were displaced in relative frequency to set the arbitrary zero frequency coincident with the position of the strongest constituent line. Best-fit Voigt profiles were used to verify the line strengths, positions, and broadening parameters of the probed H₂O features at typical combustion temperatures. Peak absorption values ranged from 20 to 40% for both lines for typical flame conditions. The signal-to-noise (S/N) ratio of line 1 was approximately 2–3 times larger than that for line 2 due to the significantly larger amplitude noise present in the beam from the 1343-nm laser that was operated near threshold conditions. The slight asymmetric structure observed in the 1392-nm residual trace, the difference between the data and the best fit, suggests possibility of higher order collisional effects due to finite collision durations[7] or correlations between the collisional width and the molecular velocity.[8]

Figure 6 compares the temperatures in the flame determined from measured line intensities obtained from single scans of H₂O lineshapes recorded every 500 μs and from peak absorption measurements recorded every 1 μs with values determined from radiation-corrected thermocouple measurements. The deviation between the temperature at the centerline and the temperature that would yield the measured absorption for the given path length and path-averaged mole fraction was typically 2–7%. Variations in the line shape function along the beam path were negligible.

The maximum variation between temperatures determined from integrated and peak line intensities and thermocouple measurements was 7 and 11%, respectively, over the range 300–1800 K. The
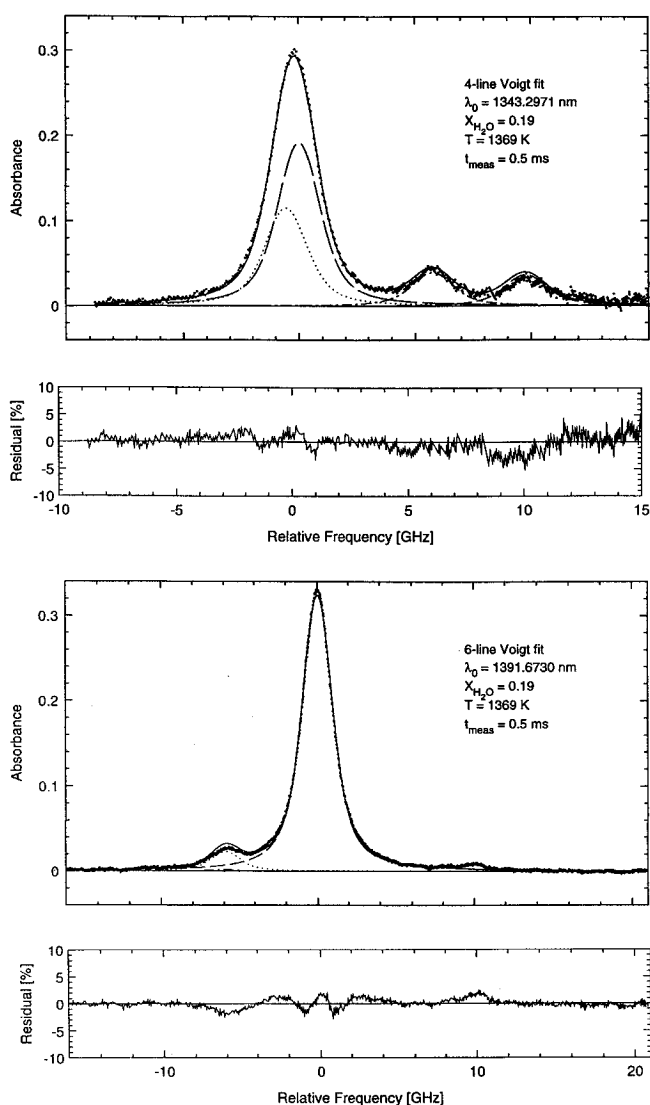
deviation between the measured values at lower temperatures in the flame (near 1100 K) was primarily due to relatively low absorption and correspondingly low S/N values. A secondary effect that may increase measurement uncertainty may be nonuniform mixing of water vapor with the N₂ shroud gas. Temperature measurements recorded in a heated cell (300–625 K, $P_{H_2O} = 20$ torr)[4] were included to show the range of conditions for which the system is applicable.

Figure 7 compares water-vapor mole fractions in the flame determined from absorption measurements X_{meas} with chemical-equilibrium values calculated at the measured temperatures X_{calc}. The measurement uncertainty in the X_{meas} values (15–25%) was due to the slight temperature fluctuations in the flowfield, uncertainties in the tabulated line strengths at high temperatures,[6] and fluctuations in the inlet gas flow rates. As in the temperature measurements, the uncertainties in the X_{meas} values were higher for flowfields with lower water-vapor concentrations. The determination of mole fraction from a measured line intensity depends directly on the corresponding temperature-dependent line strength, whereas a determination of gas temperature depends on the ratio of line strengths [Eqs. (4) and (5)]. Thus, temperature measurements are less dependent on uncertainties in individual line strength values.

Figure 8 illustrates the relative change in the measured absorption coefficient due to variations in the laser frequency, $\Delta\nu_{max}$, from

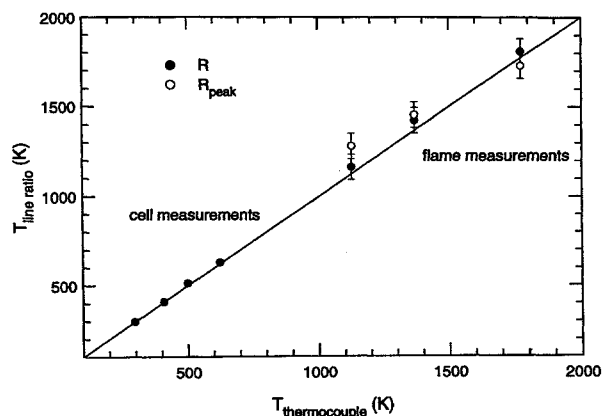Fig. 6 Comparison of temperatures measured in the H_2-O_2 flame determined from H_2O line ratios using scanned- (solid circle) and fixed- (open circle) wavelength absorption measurements and from thermocouples; the low-temperature values (300–625 K) were recorded in a heated cell (P_{H_2O} = 20 torr).[4]
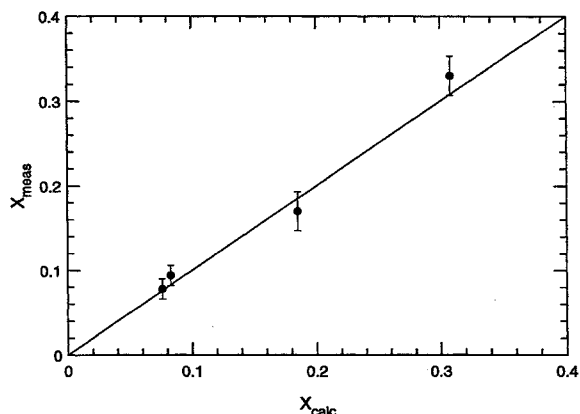

Fig. 7 Comparison of H_2O mole fractions X_{meas} determined in the H_2-O_2 flame from absorption measurements with calculated values X_{calc} at chemical equilibrium.
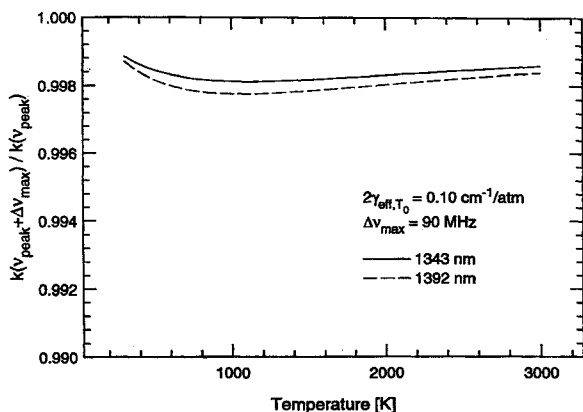

Fig. 8 Calculated variation of the spectral absorption coefficient due to frequency detuning $\Delta\nu_{max}$ from the peak absorption value, $k(\nu_{peak} + \Delta\nu_{max})/k(\nu_{peak})$, where ν_{peak} is the frequency at maximum absorption.

the peak absorption value, $k(\nu_{peak} + \Delta\nu_{max})/k(\nu_{peak})$. For a frequency detuning of 90 MHz, the variation from the peak absorption value is less than 0.24% over the measured temperature range. Thus, since data was collected only when both laser wavelengths were simultaneously within 50 MHz of the respective absorption peaks, the maximum possible detuning ($\Delta\nu_{max}$ = 50 MHz) results in an insignificant decrease in the peak absorption values and induces a negligible error on the measured temperatures.

Conclusions

A multiplexed diode-laser sensor system capable of fast, continuous, nonintrusive measurements of temperature, pressure, and the concentrations of several flowfield constituents simultaneously along a single path has been demonstrated in a premixed H_2-O_2 flame using both scanned- and fixed-wavelength absorption techniques. The ability to determine values of flowfield parameters using the fixed-wavelength absorption method significantly relaxes the wavelength tuning requirements of the probe diode lasers by eliminating the need to scan across entire absorption line shapes and offers a method for recording laser-based absorption measurements in time intervals that are determined not by laser tuning rates but by the frequency response of the detection system.

The system may be useful for a variety of applications including combustion control, process and emissions monitoring, and atmospheric studies. Furthermore, the system may be easily extended to simultaneously monitor multiple species along different paths to obtain three-dimensional flow-parameter distributions, to simultaneously monitor different, separated flowfields, or to determine multiple velocity components in moving gases through measurements of Doppler-shifted line positions.

References

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