

Application of DFB Diode Laser Sensor to Reacting Flow (I) — Estimation and Application to Laminar Flames —

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Diode laser sensor for measuring gas temperature and species concentration in combustion chamber was developed using 2.0 μm distributed feed back lasers. To evaluate the measurement sensitivity of diode laser sensor system, CO_2 survey spectra near 2.0 μm were measured and compared with the calculated one. This diode laser absorption sensor was applied to measure gas temperatures in a premixed flat flame of CH_4 -air mixture. Experimental results were in good agreement with the values by an R-type thermocouple within 6.12%. In addition, successful demonstration of measurement of gas temperature and species concentration in a soot flame showed the promising possibility of diode laser absorption sensors for practical combustion system with non-intrusive method.

Key Words : Diode Laser Sensor, 2.0 μm Distributed Feedback Laser, Combustion Measurement

1. Introduction

The problem for fuel saving and combustion control is one of the most important energy-engineering subjects and has been studied by many research groups. For improving efficiency, optimum designs of the burner and combustor are needed preferentially. Simultaneously, there is growing interest in control strategies for optimizing operating condition in combustion-driven energy. Detection and quantification are important for the characterization and the control of combustion-driven energy and the propulsion sources. As a sensor for combustion measurement, room temperature diode lasers have been utilized

for in-situ absolute measurements of species concentrations and gas temperature in a variety of combustion systems (Chou, S. I., et al., 1997; Mihalcea, R. M., et al., 1998; Miller, J. H., et al., 1993; Nagali, V., et al., 1996; Sonnenfroh, D. M., et al., 1997; Upschulte, B. L., et al., 1999). These lasers are very attractive for practical applications owing to their robustness, compactness, reasonable cost, compatibility with optical-fiber components, and relative ease of use (Mihalcea, R. M., et al., 1998).

These advantages of diode laser give us motivation of trying to establish effective control system in combustion-driven energy.

Important information could be obtained from measuring CO_2 and H_2O in the combustion field. CO_2 and H_2O are major combustion products in case of carbon-hydrogen fuel combustion. Especially, CO_2 is currently under consideration for future emission regulations because of its contribution to the greenhouse effect.

A diode laser sensor system capable of mea-

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suring CO₂ and H₂O concentrations, therefore, might be applicable to combustion control and monitoring systems for low emission and stable combustion.

Absorption spectroscopy provides the most direct method to measure absolute concentration. Absorption techniques provide measurements averaged over a path but do not point measurements. However, the spatial resolution in the plane perpendicular to the laser beam direction is limited by the laser beam diameter that can be rather small (Eckbreth, A. C., 1987).

Diode laser-based absorption spectroscopy techniques have generally been used to probe transitions of selected species with electronic or vibrational bands that overlap the spectral regions. Development of InGaAsP material has extended the measurable wavelength to 1.3~1.5 μm, allowing access to important combustion species such as CO, CO₂ and H₂O.

Further developments in material of diode laser have extended the measurable wavelength to 2.0 μm. This makes it possible to measure stronger transitions (Arroyo, M. P., et al, 1994; Baer, D. S., 1994). Actually, the line intensities of rotational transition near 2.0 μm are approximately 70 times stronger than those near 1.5 μm (Baer, D. S., et al., 1995). Development of absorption sensors near 2.0 μm, therefore, is very important for measuring unstable reacting flow. The objective of present work is to develop a diode laser absorption sensor sweeping H₂O and CO₂ transitions near 2.0 μm and to apply this absorption sensor to real combustion system.

2. Theory

The measurement technique is based on the absorption of monochromatic near-IR laser radiation. The transmission of a probe beam of light through absorbing medium obeys the Beer-Lambert relation as follows;

$$T = \left(\frac{I}{I_0} \right)_{\nu} = \exp(-k_{\nu}L) \quad (1)$$

where, L is pass length in the medium, I_0 is the incident intensity of probe beam, I is intensity

after propagation through a length L of the absorbing medium, and k_{ν} is spectral absorption coefficient at frequency ν . The spectral absorption coefficient (cm⁻¹) comprising N_j overlapping transitions in a multi-component environment of K species can be expressed as

$$k_{\nu} = P \sum_{j=1}^K X_j \sum_{i=1}^{N_j} S_{i,j}(T) \Phi_{\nu,i,j} \quad (2)$$

where, P (atm) is the total pressure of the absorbing species, X_j is the mole fraction of j species, $S_{i,j}(T)$ (cm⁻²/atm) is the line strength transition i and species j , and $\Phi_{\nu,i,j}$ (cm) is the respective line shape function of transition i at frequency ν . Its spectral integral over frequency is unity. The line shape function depends on temperature through the Doppler broadening and on both pressure and temperature through the collision broadening.

In general, spectral distribution can be explained by the combination of Doppler- and collision broadening. This composed distribution is called as Voigt profile and expressed as

$$\Phi(\nu) = \int \Phi_D(u) \Phi_c(\nu) du \quad (3)$$

The shape of spectral distribution depends on the molecular temperature, pressure and concentration. Therefore, it is possible to obtain the information of parameters that determine the Voigt profile by the measurement and analysis of the Voigt profile shape. The Voigt parameter has been defined as the ratio of Doppler broadening to collision one.

$$\alpha = \frac{\sqrt{\ln 2} \Delta \nu_D}{\Delta \nu_D} \quad (4)$$

The line strength at any other temperature T may be calculated from

$$S_i(T) = N_L \left(\frac{273}{T} \right) \left(\frac{\pi e^2}{m_e c^2} \right) \left(\frac{g_{l,i}}{Q(T)} \right) f_i \times \exp\left(\frac{-hcE_i''}{kT} \right) \left\{ 1 - \exp\left(\frac{-hc\nu_{0,i}}{kT} \right) \right\} \quad (5)$$

where, N_L (cm⁻³) is the Loschmidt's number, h (Js) is Planck's constant, k (J/K) is Boltzmann's constant, c (cm/s) is the speed of light, $Q(T)$ is the molecular partition function, $g_{l,i}$ is the lower state degeneracy of transition i , E_i'' is the lower

state energy, and f_i is the oscillator strength of transition i .

Line strength at temperature T can be scaled from line strength at T_0 .

$$S_i(T) = S_i(T_0) \frac{T_0}{T} \frac{Q(T_0)}{Q(T)} \exp\left[-\frac{hcE_i'}{k} \left\{\frac{1}{T} - \frac{1}{T_0}\right\}\right] \times \left[\frac{1 - \exp(-hc\nu_{o,i}/kT)}{1 - \exp(-hc\nu_{o,i}/kT_0)} \right] \times \left[\frac{1 - \exp(-hc\nu_{o,i}/kT)}{1 - \exp(-hc\nu_{o,i}/kT)} \frac{1 - \exp(-hc\nu_{o,z}/kT_0)}{1 - \exp(-hc\nu_{o,z}/kT)} \right] \quad (6)$$

The strategy for measuring the temperature of the gas is based on the intensity ratio of two-absorption line.

$$R = \frac{T_1(T_0)}{S_2(T_0)} \exp\left[-\frac{hc}{k}(E_1'' - E_2'')\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \times \frac{1 - \exp(-hc\nu_{o,1}/kT)}{1 - \exp(-hc\nu_{o,2}/kT)} \frac{1 - \exp(-hc\nu_{o,2}/kT_0)}{1 - \exp(-hc\nu_{o,1}/kT_0)} \quad (7)$$

$$= \frac{S_1(T_0)}{S_2(T_0)} \exp\left[-\frac{hc}{k}(E_1'' - E_2'')\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

Thus, the intensity ratio for a given pair of lines is a function of temperature only. The temperature can be taken by intensity ratio through experimental measurement.

$$T = \frac{hc}{k}(E_1'' - E_2'') \left[\ln \frac{1}{R} \frac{S_1(T_0)}{S_2(T_0)} + \frac{hc}{k}(E_1'' - E_2'') \frac{1}{T_0} \right]^{-1} \quad (8)$$

The partial pressure of gas can be obtained from Eqns. (1) and (2) if the temperature, line strength, and pass length are given. Line strengths and positions for absorption species at each temperature have been taken from the recently released U. S Air Force HITEMP (high-temperature version of HITRAN) and HITRAN98. This HITEMP database is the most extensive detailed spectral modeling code available for CO₂ and H₂O at high temperature (Allen, M. G., et al., 1996).

When spatially resolved measurements are required in non-uniform flows, this line-of-sight method may represent a significant problem and require complex reconstruction algorithms (Pett, R. S., et al., 1998). However, a reasonable estimate of the average value of gas mole fraction or temperature at the combustor exit can be sufficient to monitor the health of the combustor (Seitman, J. M., et al., 2000).

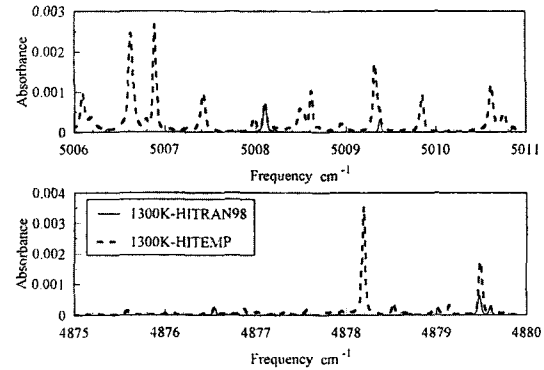


Fig. 1 Calculated survey spectra of H₂O in the 5006-5011 cm⁻¹ and 4875-4880 cm⁻¹ spectral region at 1300K using HITRAN98 and HITEMP

3. Spectra

Spectral absorption coefficients were calculated according to Eqn. (2). The summations over spectral lines were performed for all transitions with center frequencies within 5 cm⁻¹.

Figure 1 shows calculated survey spectra of H₂O in the 5006-5011 cm⁻¹ and 4875-4880 cm⁻¹ spectral region at 1atm. HITRAN98 and HITEMP were compared at 1300K, which is typical working temperature in the combustor. Many absorption lines could be observed from HITEMP database, which do not exist in the HITRAN98. Actually, it was confirmed experimentally that the HITEMP database is more realistic than HITRAN98 database at high temperature though it is not expressed here. HITEMP database for H₂O absorption line was used in present work.

4. Experimental Setup

Figure 2 shows the diagram of absorption coefficient measurement using diode laser sensor system. There are two DFB lasers (5 mW), operating near 1996 nm and 2050 nm, respectively. The output of each laser was split into three fibers, one for direct absorption measurement, one for reference beam and one for fiber ring interferometer (FSR=1.09 GHz). The direct absorption measurements are carried out using two optical fibers, one from diode laser source and the

other from light collecting fiber, which is connected to beam splitter (1996/2050 nm), and electronics.

Figure 3 shows the experimental set up for combustion measurements using diode laser ab-

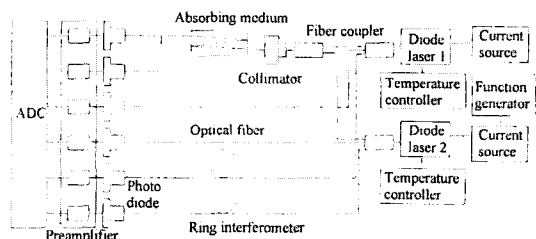


Fig. 2 Diagram of absorption coefficient measurement system

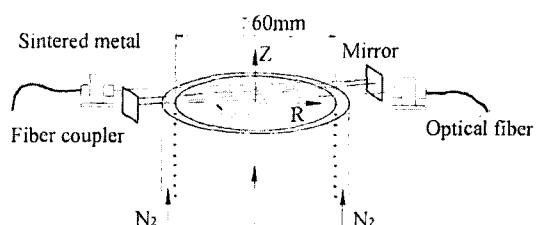


Fig. 3 Experimental set-up of premixed, laminar flat flame burner

sorption sensors. The temperature and concentration of species at the post-flame region were measured on a premixed flat-flame with 6 cm diameter. Mixtures of fuel and air were supplied into the burner. CH₄ and C₂H₂ were used as fuel. The measuring performance of diode laser absorption sensor was estimated for CH₄-air premixed flame in the flat-flame burner. Then, absorption coefficient was measured in the soot flame region of C₂H₂-air premixed flame. The equivalence ratio of CH₄-air premixed flame was changed between 0.69 and 1.07. Post-flame temperature was also measured at the center of the burner port using a R-type thermocouple of 0.1 mm wire diameter. The probe beams for the direct absorption measurements were reflected 5 times by mirrors to make high absorption pass/volume ratio. Thus, the pass length for the flat-flame was 30 cm.

5. Experimental Results & Discussions

The objectives of present work are to develop novel diode laser absorption sensor and to apply

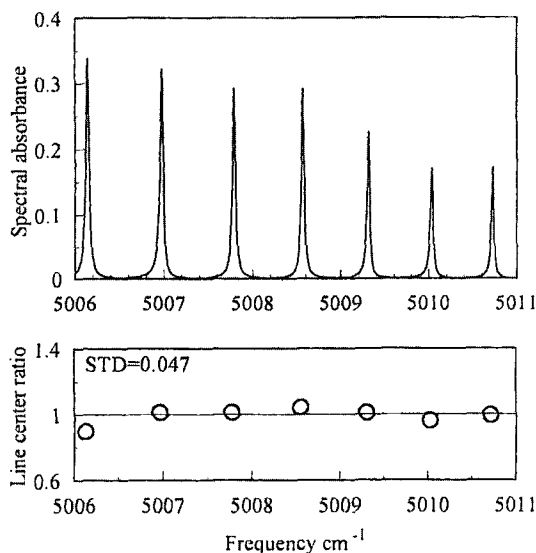


Fig. 4(a) Measured CO₂ survey spectra between 5005-5011 cm⁻¹ at 573K and a comparison of measured and calculated (HIT-RAN98) line center absorbances. (10% CO₂, 85-95 Torr)

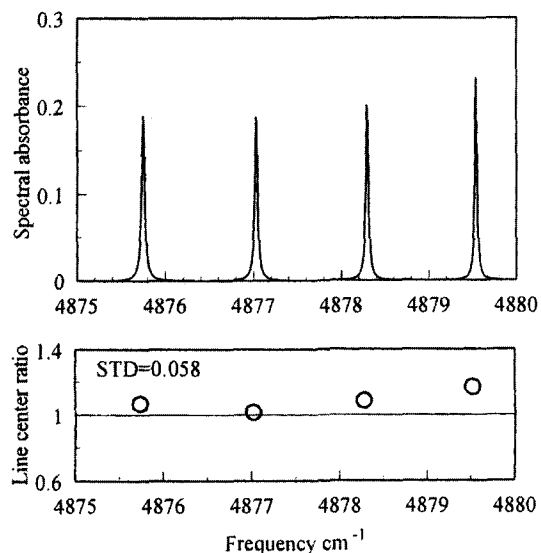


Fig. 4(b) Measured CO₂ survey spectra between 4875-4880 cm⁻¹ at 573K and a comparison of measured and calculated (HIT-RAN98) line center absorbances. (10% CO₂, 85-95 Torr)

it to real combustion system. Therefore, it is necessary to estimate the performance of developed diode laser sensor before applying it to real combustion system. Because CO_2 is better than H_2O to control the partial pressure and temperature, the CO_2 absorbances at 573 K near $2.0 \mu\text{m}$ were measured. Multi-pass cell, pass length of 250 cm, was used for high pass length/volume ratio.

Figures 4(a) and (b) show the measured CO_2 survey spectra and the ratio of measured and calculated line center absorbances in spectral range from $5006\text{--}5011 \text{ cm}^{-1}$ and $4875\text{--}4880 \text{ cm}^{-1}$, respectively. Because the HITEMP and HITRAN databases are almost identical for CO_2 of several hundred Kelvin temperature circumstance, HITRAN98 was used for CO_2 absorbance calculation. In general, good agreement with calculation results was found and its averaged discrepancy is 4.7% and 5.8%, respectively. These discrepancies between experiments and calculations resulted from the uncertainty of setting partial pressure of CO_2 , uncertainties in the HITRAN98 database, and measuring errors. However, the measured CO_2 survey spectra near $2.0 \mu\text{m}$ by diode laser absorption sensors show good agreement with HITRAN database.

Because combusting flow has multiple gas components and also has temperature and concentration gradients, abrupt density gradient restricts pass length extension through reflecting by mirrors. Here, the performance of diode laser sensor was estimated for laminar flame formed in the flat-flame burner.

The wavelengths of DFB lasers were scanned over selected H_2O transitions shown in Table 1. The repetition rate of sweeping was about 1.5 kHz. Temperature was measured from the ratio of two absorption intensities of H_2O transitions.

Figure 5 shows the single sweep of H_2O obtained from CH_4 -air premixed flame in the flat-flame burner. The residual shows the difference between the direct absorption data and the Voigt profile. The H_2O transition was (021)-(010) transition at 4878.193 cm^{-1} . Supplied equivalence ratio and measured temperature by R-type thermocouple were 0.75 and 1385.82K, respectively.

Table 1 Characteristics of absorption transitions

Species	Transition Frequency (cm^{-1})	Line Strength (1200K) ($\text{cm}^{-2}/\text{atm}$)	Transition
H_2O	4878.193	1.08E-3	(021)-(010)
	5008.101	4.91E-4	(011)-(000)

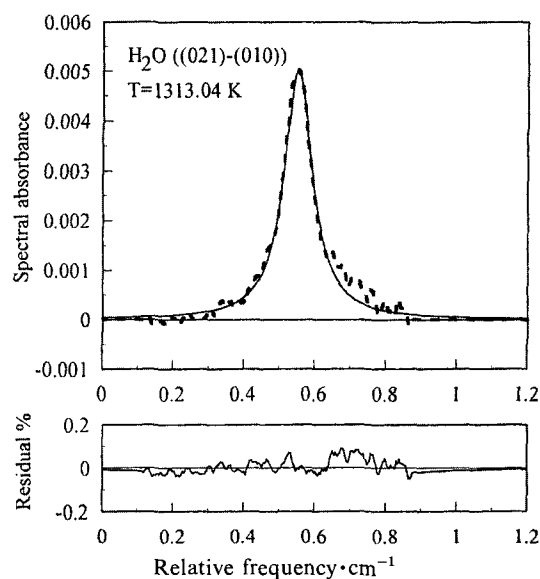


Fig. 5 Measured H_2O transition obtained from CH_4 -air premixed flame in the flat-flame burner at an equivalence ratio of 0.75

Measured temperature by diode laser sensor was 1313.04K as shown in Fig. 5. Considering the difference between point and line-averaged measurement, the discrepancy between two-measurement methods seems acceptable. The discrepancy near center frequency of transition resulted from beam steering due to flow fluctuation. Therefore, a fitted Voigt profile was used for absorption coefficient integral in the measurement of gas temperature and species concentration.

Figure 6 shows the gas temperatures measured in the post-flame region of laminar flat-flame by the thermocouple and diode laser sensors as a function of equivalence ratio. CH_4 was used as fuel. The measured temperatures were nearly independent of stoichiometry due to the heat loss to the burner port. The uncertainty of the thermocouple measurements primarily depends on

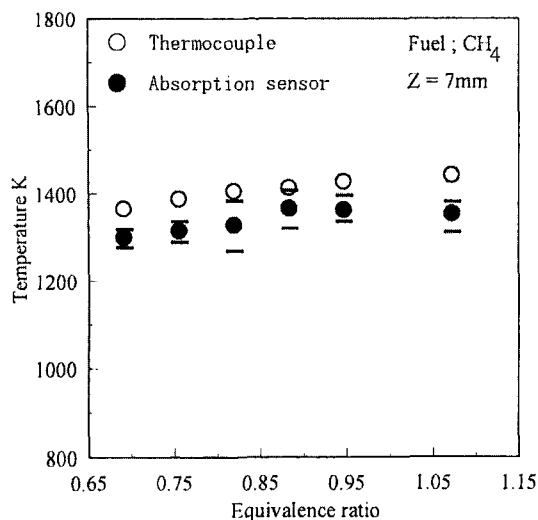


Fig. 6 Comparison of measured temperature using absorption sensor to thermocouple in the CH_4 -air flame as a function of equivalence ratio

radiation loss, which was estimated about 2-3%. The average and maximum difference between temperatures measured by the diode laser sensors and by the thermocouple was estimated 4.91% and 6.12%, respectively. At rich condition over $\phi=1.07$, there is a temperature gradient in the boundary layers of used flat-flame burner. Therefore, it was hard to estimate the performance of diode laser sensor for richer conditions. Considering the maximum discrepancy to be 6.12% at $\phi=1.07$, temperature measurement using diode laser sensor is acceptable.

Based on above result, it was confirmed that diode laser sensor system which sweep near $2.0 \mu\text{m}$ is applicable to temperature and absorption coefficients measurement in the multi-pass cell or laminar flame. However, it should be noted that practical combusting environment has soot, droplets, and etc. To apply this diode laser sensor to practical combustion system, it is necessary to estimate the performance for various combustion conditions. Therefore, the absorption coefficient measuring performance was demonstrated in the C_2H_2 -air premixed flame, which emits much soot.

Figure 7 shows the single sweep over the

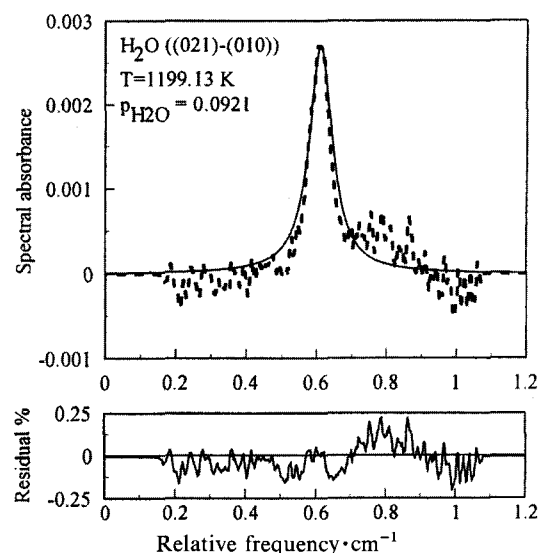


Fig. 7 Measured H_2O transition obtained from C_2H_2 -air premixed flame in the flat-flame burner at an equivalence ratio of 1.34

(021)-(010) transition of H_2O obtained from C_2H_2 -air premixed flame in the flat-flame burner at equivalence ratio of 1.34. The residual shows the difference between the direct absorption data and the Voigt profile. Under this equivalence ratio condition, the yellow flame due to emitting soot can be observed over all the combusting region. Measured temperature and H_2O concentration were 1199.34K and 9.21%, respectively. Direct absorption coefficient data were in good agreement with Voigt profile from center frequency to bandwidth, even though relatively large discrepancy was detected in the low absorption coefficient region, where absorption data fluctuates, in the single sweep. This fluctuating discrepancy resulted from beam steering due to flow fluctuation and emitting soot. Since the measured temperature by thermocouple in the burner port center was 1178.49K, temperature measurement using diode laser sensor in the soot flame is acceptable. However, measured H_2O concentration is relatively larger than equilibrium calculation at measured temperature (7.38%). This discrepancy is thought to be resulted from either in error of HITEMP database and/or pass length estimation.

6. Conclusions

Diode laser absorption sensor operating near $2.0\ \mu\text{m}$ was developed. The system was applied to measure gas temperature and species concentration in the post-flame region of a premixed laminar flat-flame of CH_4 -air mixture and C_2H_2 -air mixture. It was found that measured temperatures using the diode laser sensors were consistent with the measured values by the thermocouple in the post flame of CH_4 -air flat-flame. In addition, as a result of C_2H_2 -air soot flame experiment, temperature measurement using diode laser absorption sensor is acceptable, even though H_2O mole fraction measurements showed relatively large discrepancy with calculated equilibrium values. These results demonstrate the ability of simultaneous non-intrusive measurement of gas temperature and concentration as well as the possibility of application to practical combustion system.

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