



A sensor for measurements of temperature and water concentration using a single tunable diode laser near 1.4 μm

Tingdong Cai^a, Hui Jia^a, Guishi Wang^a, Weidong Chen^b, Xiaoming Gao^{a,*}

^a Anhui Institute of Optics and Fine Mechanics, The Chinese Academy of Sciences, Hefei 230031, PR China

^b Laboratoire de Physicochimie de l'Atmosphère, Université du Littoral Côte d'Opale 189A, Av. Maurice Schumann, 59140 Dunkerque, France

ARTICLE INFO

Article history:

Received 24 April 2008

Received in revised form 3 March 2009

Accepted 3 March 2009

Available online 21 March 2009

Keywords:

Diode laser

Wavelength modulation

Combustion

Water vapor

Temperature

Water concentration

ABSTRACT

Gas temperature and water concentration are measured by a tunable diode laser sensor using a single laser near 1.4 μm . Temperature is determined from the ratio of absorption of a H_2O line pair near 7079.176 and 7079.855 cm^{-1} , which are chosen using some selected criteria. The second harmonic detection of wavelength modulation spectroscopy (WMS-2f) is employed to improve the sensor sensitivity and accuracy. Normalization of the 2f signal with the 1f signal magnitude is used to remove the need for calibration and correct for transmission variation due to beam steering, mechanical misalignments, soot, and windows fouling. An optimum laser modulation depth is selected to make the WMS-2f signals of both lines as big as possible for the target test conditions. The influence of total pressure and water mole fraction is evaluated through theoretical simulations. The validation of the sensor is conducted in a controlled static cell, yielding an accuracy of 1.06% temperature and 1.9% for H_2O concentration. Burner experiments demonstrate the accuracy (1.2% for temperature and 3.2% for H_2O concentration) and potential utility of the system for combustion diagnosis.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

A tunable diode laser (TDL) sensor based on absorption spectroscopy can provide a fast, sensitive, non-intrusive, and reliable method for *in situ* measurements of multiple flow-field parameters such as temperature, concentration, pressure and velocity in various harsh environments [1]. Water vapor (H_2O) is one of the primary hydrocarbon combustion products and has a rich absorption spectrum throughout the infrared region, as shown in Fig. 1. Furthermore, the well-developed telecommunication laser technology overlaps with rovibrational spectrum of H_2O in the near infrared (NIR) [2]. Hence H_2O is often chosen as the target absorbing species in combustion diagnosis. For example, Furlong et al. [3] developed a TDL sensor using two H_2O transitions at 1.34 and 1.39 μm for combustion control of an acoustically forced dump combustor; Teichert et al. [4] measured water vapor and gas temperature in a coal fired power-plant using water transitions near 810 nm; Liu et al. [5,6] used multiplexed fiber-coupled diode lasers to measure temperature rapidly by two near-infrared water absorption features in gaseous flows; Reiker et al. [7] presented a near-infrared diode laser sensor that is capable of measuring time-varying gas temperature and water vapor concentration based on two water spectral features near 7203.9 and 7435.6 cm^{-1} ; Liu et al. [8] determined the

gas temperature in the exhaust of an industrial gas turbine using two water transitions at 7429.72 and 7454.45 cm^{-1} ; Li et al. [9,10] measured temperature and H_2O concentration in shock tubes based on fixed-wavelength laser absorption of two H_2O transitions near 7185.60 and 7154.35 cm^{-1} .

In these previous studies of temperature measurements, the most frequently used dual-laser method has some disadvantages with regard to cost and system complexity. If transitions should be chosen suitably, it is possible to perform two-line absorption thermometry using a single diode laser. A few TDL temperature sensors using a single laser have been reported previously due to the infrequent coincidences of laser wavelengths and water transitions; for example, Arroyo and Hanson [11] developed a single-laser sensor using a H_2O line pair near 1.38 μm ; Gharavi and Buckley [12] measured the temperature and H_2O concentration simultaneously by a single diode laser near 1.477 μm ; recently, Zhou et al. [13–15] systematically analyzed the water vapor spectrum in the 1–2 μm region and developed two single TDL sensors, one using direct absorption [13] and the other using a scanned-wavelength technique with wavelength modulation and second harmonic (2f) detection [14]. By using a single diode laser, the sensor system is simplified and the cost is reduced.

In this paper, a sensor using a single NIR diode laser based on second harmonic detection of scanned-wavelength modulation spectroscopy (WMS-2f) is designed to measure gas temperature and H_2O concentration in a flame, so as to monitor the combustion. This design can reduce the cost of the system compared

* Corresponding author. Fax: +86 551 5591560.

E-mail addresses: caitingdong@126.com (T. Cai), xmgao@aiofm.ac.cn (X. Gao).

Nomenclature

a	modulation depth, cm^{-1}
C	$1f$ -normalized WMS- $2f$ signal
E''	lower state energy, cm^{-1}
i_0	linear intensity modulation amplitude
I_0	incident laser intensity, W m^{-2}
\bar{I}_0	average laser intensity at $\bar{\nu}$, W m^{-2}
I_t	transmitted laser intensity, W m^{-2}
$H_k(\bar{\nu}, a)$	k th harmonic Fourier component
L	total path length, cm
m	modulation index
P	total pressure, atm
R	ratio of $1f$ -normalized WMS- $2f$ signals
$S_{1f}(\bar{\nu})$	magnitude of the absorption-based WMS- $1f$ signal, cm^{-1}
$S_{2f}(\bar{\nu})$	magnitude of the absorption-based WMS- $2f$ signal, cm^{-1}
S_j	line strength of the transition j , $\text{cm}^{-2} \text{atm}^{-1}$
T	gas temperature, K
x_i	mole fraction of the absorbing species i
$\alpha(\nu)$	spectral absorbance
ν	full width at half maximum of the absorption line shape
φ_j	line shape function of the transition j
$\bar{\nu}$	center frequency of the laser, cm^{-1}
$\nu(t)$	laser frequency, cm^{-1}
$\tau(\nu)$	transmission coefficient
ω	wavelength modulation angular frequency, rad s^{-1}

with the mode of multiplexed lasers. The absorption transitions of H_2O around $1.4 \mu\text{m}$ are analyzed to select the optimum line pair because the overtone and combination bands of H_2O near $1.4 \mu\text{m}$ are relatively free of interference from absorption by the major combustion products and commercially available telecommunication fiber-coupled diode lasers and optics are readily available. The wavelength scan of the selected H_2O line pair can mitigate the problems of variation of the power and wavelength of the laser caused by the temperature, driving current, working environment, etc., which exist in fixed-wavelength approach. Validation of the sensor with controlled experiments and demonstration of its use in a laboratory flame is given. A line pair near $1.413 \mu\text{m}$ is selected for the TDL sensor using some selective rules established follow-

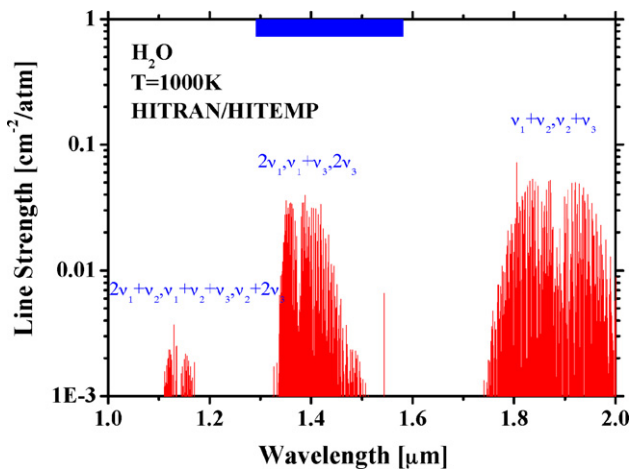


Fig. 1. Survey spectra of H_2O at 1000 K in the NIR region based on Hitran/Hitemp database.

ing the design criteria previously reported in [8,13–15]. The laser modulation depth is optimized to maximize the WMS- $2f$ signals of both lines and to simplify signal interpretation. The influence of total pressure and water concentration is evaluated. The TDL sensor for gas temperature and H_2O concentration measurements is first validated in a heated cell (500–1000 K) containing H_2O –air mixture. Measurements in a laboratory flame at atmospheric pressure are then described to demonstrate the potential of this sensor for combustion application.

2. Theoretical principles

Following the theory of WMS including real diode laser performance [16,17], here we rewrite the equations for the WMS signals into a form providing the magnitude of the $2f$ and $1f$ signals. The diode laser injection current is sinusoidally modulated with angular frequency $\omega = 2\pi f$ to produce laser frequency modulation (FM)

$$\nu(t) = \bar{\nu} + a \cos(\omega t), \quad (1)$$

where $\bar{\nu}$ is the center frequency of the laser and a is the modulation depth.

For optical thin samples ($\alpha(\nu) < 0.1$), the transmission coefficient $\tau(\nu)$ of monochromatic radiation through a uniform medium of length L [cm] can be approximated as

$$\tau(\nu) = \left(\frac{I_t}{I_0} \right) = \exp[-\alpha(\nu)] \approx 1 - \alpha(\nu) = 1 - P x_i L \sum_j S_j(T) \varphi_j \quad (2)$$

where I_t and I_0 are the transmitted and incident laser intensities, $\alpha(\nu)$ represents the spectral absorbance, P [atm] is the total pressure, x_i is the mole fraction of the absorbing species, S_j [$\text{cm}^{-2} \text{atm}^{-1}$] is the line strength of the transition, φ_j [cm] is the line shape function which is normalized such that $\int \varphi_j(\nu) d\nu \equiv 1$ and T [K] is the gas temperature. It is a periodic even function in ωt and can be expanded in a Fourier cosine series:

$$\tau[\bar{\nu} + a \cos(\omega t)] = \sum_{k=0}^{\infty} H_k(\bar{\nu}, a) \cos(k\omega t), \quad (3)$$

where the components $H_k(\bar{\nu}, a)$ can be described as

$$H_0(\bar{\nu}, a) = 1 - \frac{P x_i L}{2\pi} \int_{-\pi}^{\pi} \sum_j S_j \varphi_j(\bar{\nu} + a \cos \theta) d\theta, \quad (4)$$

$$H_k(\bar{\nu}, a) = -\frac{P x_i L}{\pi} \int_{-\pi}^{\pi} \sum_j S_j \varphi_j(\bar{\nu} + a \cos \theta) \cos k\theta d\theta. \quad (5)$$

H_k is directly proportional to species concentration x_i and path length L when the line shape functions do not vary for the range of conditions found in the applications [16]. Note that in addition to the absorption parameters, H_k also depends on the modulation depth a , this effect can be mitigated by choosing a proper modulation index m , which is defined as

$$m = \frac{a}{\Delta\nu/2}, \quad (6)$$

where $\Delta\nu$ is the full width at half maximum (FWHM) of the absorption line shape [18].

For an isolated transition, it is well known that H_2 is maximized while H_1 and H_3 are zero at line center. Hence near the line center, the dominant term of WMS- $2f$ signal is the second Fourier component H_2 , and H_0 , which is close to unity, is the dominant term of WMS- $1f$ signal [9]. Thus the magnitude of the absorption-based WMS- $2f$ signal, $S_{2f}(\bar{\nu})$ and $S_{1f}(\bar{\nu})$ measured by a lock-in amplifier

can be reduced as

$$S_{2f}(\bar{\nu}) \approx \frac{G\bar{I}_0}{2} H_2(\bar{\nu}) = -\frac{G\bar{I}_0}{2} \cdot \frac{PS(T)x_i L}{\pi} \int_{-\pi}^{\pi} \varphi(\bar{\nu} + a \cos \theta) \cos 2\theta d\theta, \quad (7)$$

$$S_{1f}(\bar{\nu}) \approx \frac{G\bar{I}_0 i_0}{2}. \quad (8)$$

where G is the optical–electrical gain of the detection system, \bar{I}_0 is the average laser intensity at $\bar{\nu}$, i_0 is the linear intensity modulation amplitude.

From Eqs. (7) and (8), the WMS-1f-normalized absorption-based WMS-2f signal is given by

$$C = \frac{S_{2f}}{S_{1f}} = \frac{1}{i_0} H_2(\bar{\nu}). \quad (9)$$

By the normalization of the 2f signal with the 1f signal magnitude, common terms such as laser intensity, signal amplification, lock-in gain and laser transmission variation can be eliminated. The 1f-normalized WMS-2f signal, C , is a function of laser parameters (i_0 , a) and gas parameters (P , T , x_i) only. The laser parameters can be determined before the measurements, thus the comparison should be made directly between the WMS-2f simulations and measurements and eliminating the need for scaling between the two [9,16].

Gas temperature can be obtained from the ratio of 1f-normalized WMS-2f signals at two selected wavelengths

$$R = \frac{C_2}{C_1} = \frac{S_2(T) \int_{-\pi}^{+\pi} \varphi(\bar{\nu}_2 + a \cos \theta) \cos 2\theta d\theta}{S_1(T) \int_{-\pi}^{+\pi} \varphi(\bar{\nu}_1 + a \cos \theta) \cos 2\theta d\theta} \quad (10)$$

which is closely related to the ratio of absorption line strengths. If the total pressure is measured by a pressure transducer, the gas temperature can be inferred by comparison of the measured ratio R with the simulation of the ratio as a function of temperature at the measured pressure. After the temperature is known, the species concentration can be determined from either of the 1f-normalized WMS-2f signal magnitudes at two selected transitions.

3. Sensor development

3.1. Line selection

An important step in sensor development is the line selection. Sensor performance can be greatly improved by selecting optimum transition. Systematic line selection criteria for absorption-based thermometry have been developed in literature [8,13–15], here we briefly list the rules used in the selection based on the HITRAN 2004 database [19].

3.1.1. Position of the line pair

The line pair must be located near 1.4 μm , where the $\nu_1 + \nu_3$ combination band of H_2O absorption spectra overlaps with the most common telecommunication band. In this region, robust fiber-coupled single-mode diode lasers and optical fibers are widely available [2].

3.1.2. Line separation of the pair

At present time the typical rapid-tuning range of the telecommunication quality single-mode DFB diode laser commercially available is 0–2 cm^{-1} . Here the spectral separation of the two transitions should range between 0.3 and 1 cm^{-1} for a suitable line pair, so as to insure that the selected lines are close enough together to be encompassed by a single-laser scan, yet far enough apart to avoid overlap.

3.1.3. Absorption strength of the pair

The peak absorbance of the pair must be large enough to ensure a good signal-to-noise ratio (SNR), but in order to accord the “weak transition” assumption associated with wavelength modulation measurements, the peak absorption should be less than ~ 0.1 . The value at different conditions should be calculated by checking the needed parameters in HITRAN/HITEMP 2004 database.

3.1.4. Relation between the ratio of WMS-2f signals and temperature

As shown in Eq. (10), the ratio of WMS-2f signals is closely related to the ratio of the individual line strengths. In order to obtain temperature of the gas through the measurement of the ratio of WMS-2f signals, the relation between them must be monotone. Hence the line strength ratio also must be single value with temperature in the expected range

3.1.5. Sensitivity of WMS-2f signals’ ratio to temperature

It is known that the relative sensitivity of absorption strength ratio to temperature is

$$\left| \frac{\partial R/R}{\partial T/T} \right| = \left(\frac{hc}{k} \right) \frac{|E'_1 - E'_2|}{T}, \quad (16)$$

where E' is the lower state energy (cm^{-1}). It is generally desirable that the temperature sensitivity be as high as possible, resulting in a more accurate sensor. In order to have high temperature sensitivity, the line pair should have a larger difference in lower state energy. If the 2f peak heights can be determined within 2%, in order to obtain a temperature accuracy of 5% in the temperature range of 500–1500 K, the constraint on minimum lower state energy difference could be given as follows while the influence of line shape function is neglected

$$\begin{aligned} |\Delta E''| &= |E'_1 - E'_2| \geq \left| \frac{dR/R}{dT/T} \right| \times T \times \frac{k}{hc} \\ &= \frac{0.02\sqrt{2}}{0.05} \times 1500 \times \frac{1}{1.4388} = 550 \text{ cm}^{-1}. \end{aligned} \quad (17)$$

3.1.6. Line shape functions of the pair

As shown in Eq. (10) the peak ratio is not only the function of temperature, but also depends on pressure and mole fraction due to the effect of the line shape function. This leads to complications and potentially added uncertainty for the measurements. This difficulty should be overcome by selected two lines with nearly identical line shape function. More specifically, the two lines should have nearly the same air-broadened halfwidth, self-broadened halfwidth and temperature-dependent coefficients.

Based on those criteria, the line pair near 7079.176 and 7079.855 cm^{-1} is selected for the WMS-2f temperature sensor. Some of their spectral parameters are listed in Table 1. Fig. 2 shows the simulated H_2O (10% water in air) direct absorption and 2f signals for the selected line pair based on these parameters. The line strength and their ratio of the pair are plotted in Fig. 3.

3.2. Optimization of modulation depth

As can be seen from Eq. (5), the WMS-2f peak height is dependent on the line shape function, φ . This dependence should cause difficulties in the temperature measurements using WMS-2f spectroscopy. In order to infer gas temperature using harmonic signals, it is desired that the peak ratio should only depend on the line strengths of the selected line pair. Fortunately, this effect of line shape function can be mitigated by choosing an optimum modulation depth, as discussed in [14].

Table 1
The selected H₂O line pair for the 1*f*-normalized WMS-2*f* sensor based on HITRAN/HITEMP 2004.

ν [cm ⁻¹]	$S@1000\text{K}$ [cm ⁻² atm ⁻¹]	γ_{air} [cm ⁻¹]	γ_{self} [cm ⁻¹]	E'' [cm ⁻¹]	$\Delta E''$ [cm ⁻¹]	n
7079.176	1.1795E-3	0.0351	0.4300	552.91	569.80	0.64
7079.855	9.4246E-4	0.0393	0.4200	1122.71		0.53

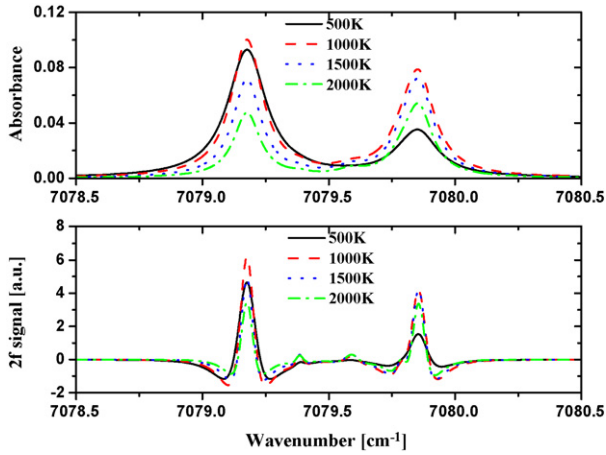


Fig. 2. Simulated direct absorption and 2*f* signals for the selected H₂O line pair using the Hitran/Hitemp database for $P=1$ atm, 10% H₂O in air, $L=20$ cm.

The simulated normalized WMS-2*f* peak heights of the selected H₂O line pair versus modulation depth at three temperatures ($T=1000, 1500$ and 2000 K; $P=1$ atm, 10% H₂O in air, and $L=20$ cm) with the spectroscopic parameters listed in Table 1 are shown in Fig. 4. As shown in this figure, the modulation depth $a_{\text{opt}}=0.076$ cm⁻¹ is optimum. The WMS-2*f* peak height has a biggish value and varies slowly with such an optimum modulation depth. Thus, the ratio of two WMS-2*f* peak heights is mainly a function of the well-known line strengths of the selected transitions.

3.3. Influence of total pressure and water mole fraction

It is known that the WMS-2*f* peak height ratio also is a function of gas composition and pressure through their effect on the line shape function. The simulated WMS-2*f* peak height ratio of the selected line pair (7079.855 cm⁻¹/7079.176 cm⁻¹) as a function H₂O mole fraction (10% H₂O in air) and total gas pressure ($P=1$ atm) at 5 different temperatures with the optimum modulation depth is shown in top and bottom graph of Fig. 5. The WMS-2*f* peak height ratio is closely related to the ratio of line strengths, and is only a weak func-

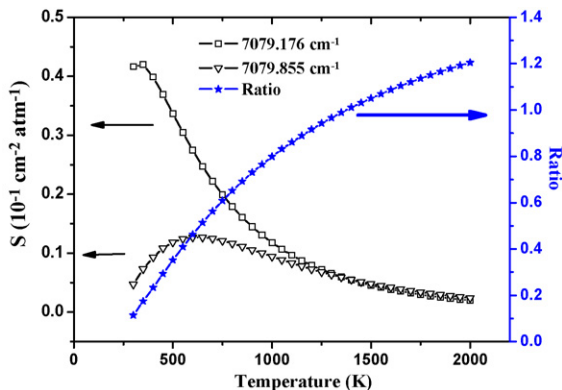


Fig. 3. Line strengths and line strength ratio as a function of temperature for the selected line pair.

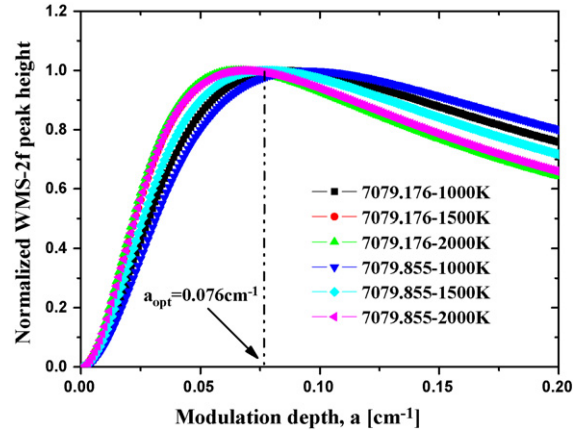


Fig. 4. Simulation of the normalized WMS-2*f* peak heights of the selected line pair versus modulation depth a ; $P=1$ atm, 10% H₂O in air, and $L=20$ cm.

tion of H₂O mole fraction and pressure. For example, at $T=1000$ K, a quadruple change in H₂O mole fraction (changes from 5% to 20%) introduced only a small change (1.5%) in the WMS-2*f* peak height ratio, and a 40% change in total gas pressure also produces a negli-

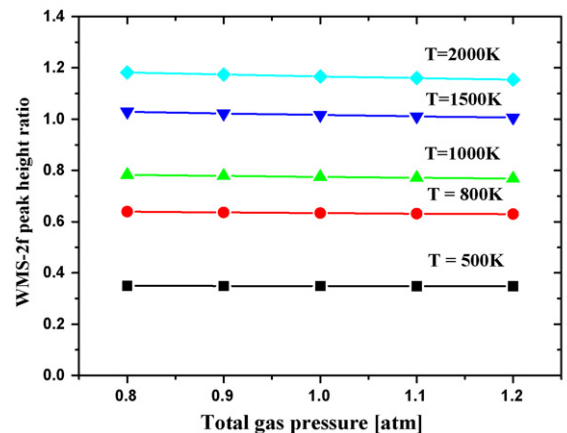
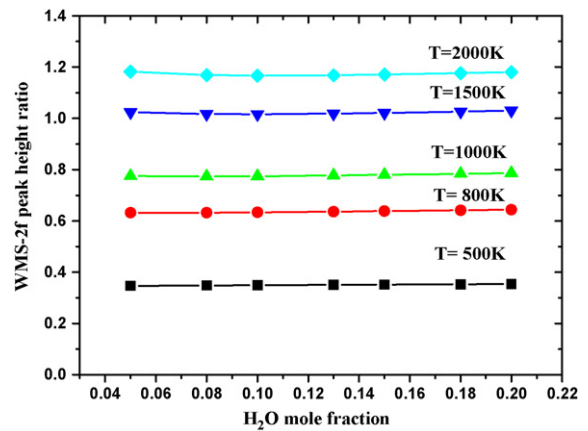


Fig. 5. The simulated 2*f* peak height ratios at different water concentrations (top, $P=1$ atm) and total pressure (bottom, $X_{\text{H}_2\text{O}}=10\%$).

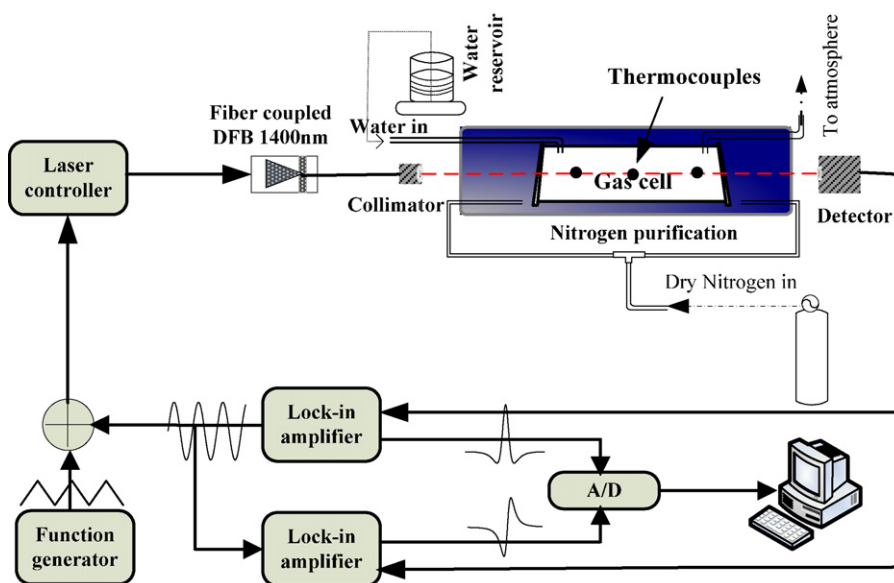


Fig. 6. Scheme of the experimental setup.

ble change (1.8%) in it. Thus, for combustion gas condition, a reliable WMS- $2f$ peak height ratio yields an accurate gas temperature.

4. Measurements demonstration on laboratory static cell

The measurements of H_2O concentration and gas temperature are first performed in a heated static cell, so as to validate the TDL sensor. The static cell can provide a quiet, transient-free environment where the total pressure, H_2O concentration and gas temperature can be precisely controlled and measured.

4.1. Experimental details

The experimental setup used for sensor validations is shown in Fig. 6. A heated static cell (38 cm long with canted wedged (1.5°) windows to avoid residual etalon fringes), equipped with a temperature controller (type SKW), is used for measurements at temperatures as high as 1000 K. Three type K thermocouples with an accuracy of $\pm 1\%$ are equally attached to the middle and both ends of the absorption cell to monitor the temperature of the gas. Maximum temperature difference along the path length is of the order of 20 K. The H_2O -air mixtures prepared in a stainless steel tank are delivered into the cell via stainless steel tubes. The tank and tubes are heated above the saturation temperature to ensure that all of the liquid water is evaporated. The gas pressures are measured by a vacuum pressure gauge with an accuracy of $\pm 1\%$ of reading.

The DFB laser (NEL NLK1E5GAAA) used in the experiments can produce ~ 10 mW of stable output power near $1.4 \mu\text{m}$. The laser is placed in a commercial laser mount (ILX Lightwave LDM-4980) and driven with a modular diode laser controller (ILX Lightwave LDC-3724). The laser wavelength is driven by a 500 Hz triangle ramp summed in an adder with a 40 kHz sine wave to provide the wavelength modulation. The sine signal is generated by a lock-in amplifier (Stanford Research Systems Model SR-830), and is also inputted into another similar lock-in amplifier as reference signal simultaneously. The laser beam is collimated by a lens, directed across the static cell, and focused by a spherical mirror onto an InGaAs detector (New Focus Model 2011). The beam path is purged by high-pure nitrogen so as to avoid the interference from ambient water vapor in room air. The detector signal is divided into

two ways, and demodulated by two lock-in amplifiers to recover the $2f$ and $1f$ signals with same time constant of $10 \mu\text{s}$. After the acquisition of $2f$ and $1f$ signals is over, the laser should be injection current tuned with a triangle ramp across the absorption features near 7079.176 cm^{-1} to obtain the direct absorption signal. This signal can be used to determine the actual H_2O concentration in the test mixture for comparison.

4.2. Results

A set of static heated cell experiments with controlled gas mixtures at precise temperatures were performed to validate the sensor accuracy and reliability for the temperature and H_2O concentration inferred from the WMS- $2f$ peak heights. All experiments are performed with H_2O -air mixture at atmospheric pressure. The measured H_2O absorption spectrum in the H_2O -air mixture at the experimental conditions of $T = 1000 \text{ K}$ is shown in Fig. 7. The line shape of the selected transition near 7079.176 cm^{-1} is fitted by a Voigt profile [20] with the Doppler FWHM fixed at a calculated value responding to the temperature. This Voigt fit provides the integrated absorbance, from which the H_2O concentration at the

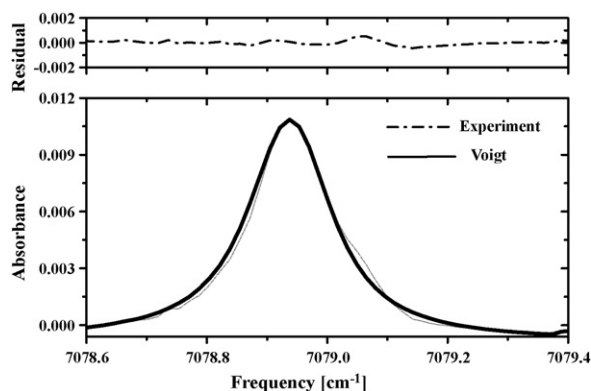


Fig. 7. Measured H_2O absorption spectrum in the H_2O -air mixture with $P=1$ atm and $T=1000 \text{ K}$. Using a best Voigt fit one yields the actual H_2O concentration. The residual of the fit is shown in the top panel.

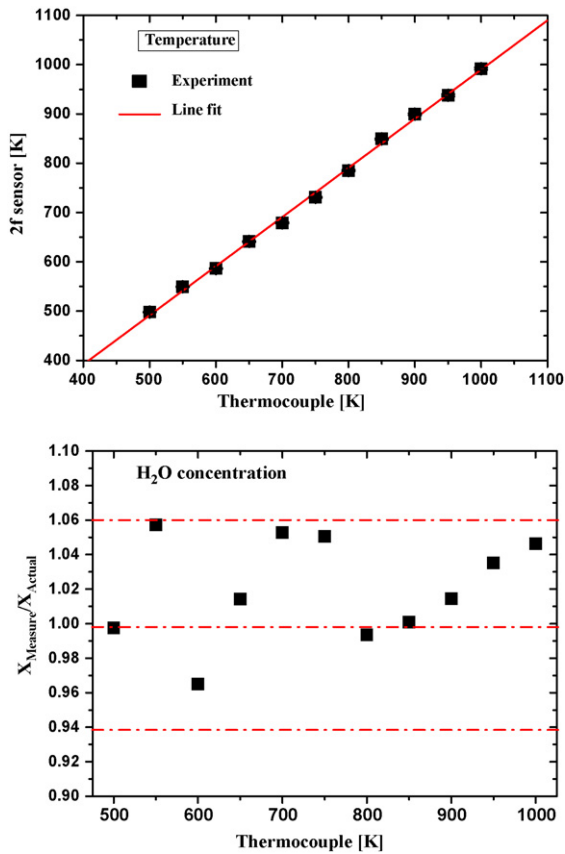


Fig. 8. Comparison of temperatures (top) and H₂O concentration (bottom) from the sensor with the actual values measured in the static cell. $P=1$ atm, $\sim 10\%$ H₂O in air, and $L=38$ cm.

experimental conditions can be calculated. The H₂O concentration may vary during the transmission due to absorption in the tank and gas handling system.

The comparison between the temperatures from the 1f-normalized WMS-2f sensor thermometry and the thermocouple readings is shown in the top graph of Fig. 8. Correlation of those measured points has an R^2 value of 0.998, and the standard deviation is 1.06% (the error bar is too small to resolve). The results indicate that the temperatures measured by the 1f-normalized WMS-2f sensor strongly agree with the thermocouple readings over the tested temperature range of 500–1000 K (average bias $\sigma_T = |T_{TDL} - T_{TC}| \sim 9$ K). The bottom graph of Fig. 8 shows the ratios of the H₂O mole fraction measured by the 1f-normalized WMS-2f sensor (x_{Measure}) and the mole fraction measured by direct absorption (x_{Actual}). Both measurements use the H₂O transition at 7079.176 cm^{-1} . The standard deviation between the measured and actual H₂O mole fraction is 1.9% over the full temperature range. The temperature and H₂O mole fraction from the 1f-normalized WMS-2f sensor agree extremely well with the thermocouple and direct absorption measurements. Those results confirm the accuracy of the sensor for combustion diagnostics. The error in Fig. 8 primarily comes from uncertainties in temperature measurements by thermocouple (1%), measured spectroscopic data (1%), and error in the base line and line shape fits (0.5%) in the direct absorption measurements. Compared with other similar systems reported in [9] (the standard deviation between the measured temperature and thermocouple reading is 1.9%, and that value between the measured and actual H₂O mole fraction is 1.4%) and [14] (the difference between the measured temperature and thermocoupled data is 10–20 K), the ability of the current sensor is well.

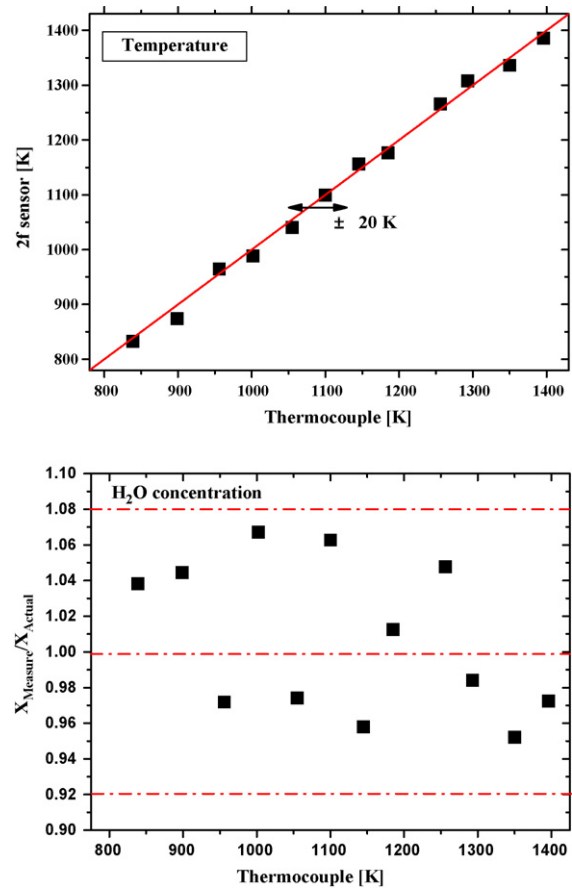


Fig. 9. Comparison of temperatures (top) and H₂O concentration (bottom) from the sensor with the actual values measured in the flame.

5. Measurements in combustion gases

In order to illustrate the potential of the 1f-normalized WMS-2f sensor for monitoring the gas temperature and H₂O concentration in the exhaust of combustion, measurements are made on a burner which can produce a constant-pressure flow-field. The uniform flame on the burner has a circular shape, and the diameter and height are 12 and 2 cm, respectively. The $1.4\ \mu\text{m}$ single-laser 1f-normalized WMS-2f sensor is driven by an external modulation, which consists of a 500 Hz triangle ramp combined with a faster 40 kHz sinusoidal signal. The beam path is purged to avoid interference from ambient water vapor. The 1f and 2f components of the transmitted laser signal are obtained by two lock-in amplifiers (Stanford Research Systems Model SR-830) with same time constant of $10\ \mu\text{s}$. A laboratory code is written in LabView for data acquisition and analysis. Once the acquisition is completed, the signal processing program transfers the captured data from on-board memory to PC memory. Data analysis, including peak finding and ratio calculation, is then performed on the accumulated data.

The sensor is aligned to probe the burned gases 1 cm above the burner. For calibrating the temperature obtained by 2f peak ratio, the thermocouple is traversed forward and back to confirm stability of the flame temperature. The combustion flows of the type studied here should be sufficient to assume an approximate uniform temperature distribution in reducing the data. Comparison of the temperatures from the WMS-2f sensor thermometry with the thermocouple readings in the flame is shown in top graph of Fig. 9. They are in good agreement over the tested temperature range of

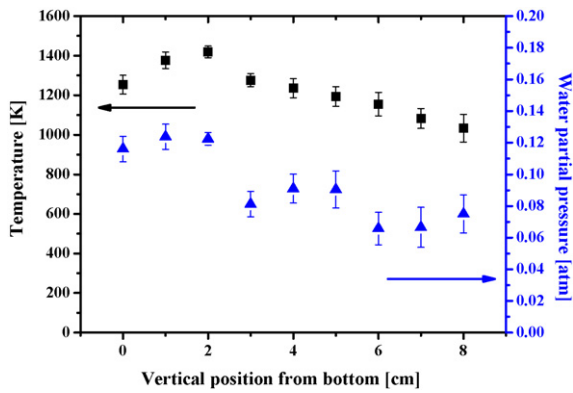


Fig. 10. The temperature (left axis) and water partial pressure (right axis) versus vertical position above the burner.

900–1200 K with an error range of ± 20 K. Correlation of those measured points has an R^2 value of 0.995, the standard deviation is 1.2%. The bottom graph of Fig. 9 shows the ratios of the H_2O mole fraction measured by the $1f$ -normalized WMS- $2f$ sensor (x_{Measure}) and the mole fraction measured by direct absorption (x_{Actual}) in the burned gas over the full temperature range. Both measurements also use the H_2O transition at 7079.176 cm^{-1} . The standard deviation between the measured and actual H_2O mole fractions is 3.2%. Temperature and water concentration are also measured across the burner along the radial way at nine vertical locations with a step length of 1 cm. Examples are shown in Fig. 10 with error bar to indicate measurement uncertainty. As shown in this figure, the vertically scanned temperature and water concentration measurements indicate large spatial variations, which certainly exist along the measurements as well.

In the temperature measurements it must be noted that the present sensor provides accurate temperature for situations in which the temperature distribution along the beam path is uniform or approximately uniform. Under other conditions where temperature changes significantly and the relative temperature profile is unknown, it may be attractive to consider multi-line thermometry [21]. Note that a rapid measurement of relative temperature change is more important than determination of an absolute value while dealing with combustion problems such as instability suppression or lean-blow-off. Hence the two-line temperature sensor can provide a potentially useful control parameter even for a condition with significant temperature gradient.

6. Conclusions

A TDL sensor using a single diode laser based on wavelength modulation spectroscopy with second harmonic detection is developed, validated in a controlled laboratory environment, and demonstrated for measurements of gas temperature and H_2O concentration on a burner. The sensor is based on two H_2O transitions near 7079.176 and 7079.855 cm^{-1} , which are selected as the best line pair for the target temperature of 500–1500 K at atmospheric pressure based on some design rules. Normalization of the $2f$ signal with the $1f$ signal magnitude is used to remove the need for calibration correction for transmission variation due to beam steering, mechanical misalignments, soot, and windows fouling. An optimum laser modulation depth is selected to make the WMS- $2f$ signals of both lines as big as possible for the target test conditions. The influence of total pressure and water mole fraction is evaluated through theoretical simulations.

Validation of the $1f$ -normalized WMS- $2f$ sensor for the temperature range of 500–1000 K ($P = 1$ atm) are performed in a static cell.

Temperature measurements are within 1.06% of the thermocouple reading, H_2O concentration measurements are within 1.9% of the expected values over the full temperature range. Then the sensor is examined in combustion gases on a burner to confirm the capability and accuracy in a real flame. Temperature measurements by the $1f$ -normalized WMS- $2f$ sensor are within 1.2% of the thermocouple reading, and H_2O concentration measurements are within 3.2% of the expected values. Good agreements between the measurements of the sensor and actual values and comparisons between the current sensor and other similar systems confirm the accuracy and potential utility of the sensor.

Acknowledgements

This research was funded by the National 863 High Technology Research and Development Program of China under Grant no. 2006AA06Z237, and the French International Programme of Scientific Cooperation. (CNRS/PICS no. 3359). The authors are most grateful to Dr. Weixiong Zhao and Dr. Zhensong Cao for their help in some stages of this work, for helpful discussion and for useful recommendations.

References

- [1] R.K. Hanson, J.B. Jeffries, Diode laser sensors for ground testing, AIAA Paper 2006-3441, June 2006.
- [2] M.G. Allen, Diode laser absorption sensors for gas-dynamic and combustion flows, Measurement Science and Technology 9 (1998) 545–562.
- [3] E.R. Furlong, D.S. Baer, R.K. Hanson, Real-time adaptive combustion control using diode-laser absorption sensors, in: Proceedings of the Combustion Institute, vol. 28, Combustion Institute, Pittsburgh, PA, 1998, pp. 103–111.
- [4] H. Teichert, T. Fernholz, V. Ebert, Simultaneous *in situ* measurement of CO , H_2O , and gas temperatures in a full-sized coal-fired power-plant by near-infrared diode lasers, Applied Optics 42 (12) (2003) 2043–2051.
- [5] J.T.C. Liu, J.B. Jeffries, R.K. Hanson, Wavelength modulation absorption spectroscopy with $2f$ detection using multiplexed diode lasers for rapid temperature measurements in gaseous flows, Applied Physics B 78 (2004) 503–511.
- [6] J.T.C. Liu, G.B. Rieker, J.B. Jeffries, R.K. Hanson, M.R. Gruber, C.D. Carter, T. Mathur, Near-infrared diode laser absorption diagnostics for temperature and water vapor in a scramjet combustor, Applied Optics 44 (31) (2005) 6701–6711.
- [7] G.B. Rieker, H. Li, X. Liu, J.B. Jeffries, R.K. Hanson, M.G. Allen, S.D. Wehe, P.A. Mulhall, H.S. Kindle, A diode laser sensor for rapid, sensitive measurements of gas temperature and water vapour concentration at high temperatures and pressures, Measurement Science and Technology 18 (2007) 1195–1204.
- [8] X. Liu, J.B. Jeffries, R.K. Hanson, K.M. Hinckley, M.A. Woodmansee, Development of a tunable diode laser sensor for measurements of gas turbine exhaust temperature, Applied Physics B 82 (2006) 469–478.
- [9] H. Li, A. Farooq, G.B. Rieker, X. Liu, J.B. Jeffries, R.K. Hanson, Near-infrared diode laser absorption sensor for rapid measurements of temperature and water vapor in a shock tube, Applied Physics B 89 (2007) 407–416.
- [10] H. Li, X. Zhou, J.B. Jeffries, R.K. Hanson, Sensing and control of combustion instabilities in swirl-stabilized combustors using diode-laser absorption, in: 42nd AIAA/ASME/ASEE Joint Propulsion Conference and Exhibit, AIAA 2006-4395, Sacramento, California, July 2006, pp. 9–12.
- [11] M.P. Arroyo, R.K. Hanson, Absorption measurements of water vapor concentration, temperature and line shape parameters using a tunable InGaAsp diode laser, Applied Optics 32 (30) (1993) 6104–6116.
- [12] M. Gharavi, S.G. Buckley, Single diode laser sensor for wide-range H_2O temperature measurements, Applied Spectroscopy 58 (4) (2004) 468–473.
- [13] X. Zhou, X. Liu, J.B. Jeffries, R.K. Hanson, Development of a sensor for temperature and water concentration in combustion gases using a single tunable diode laser, Measurement Science and Technology 14 (2003) 1459–1468.
- [14] X. Zhou, J.B. Jeffries, R.K. Hanson, Development of a fast temperature sensor for combustion gases using a single tunable diode laser, Applied Physics B 81 (2005) 711–722.
- [15] X. Zhou, X. Liu, J.B. Jeffries, R.K. Hanson, Selection of NIR water vapor transitions for in-cylinder measurement of temperature during the compression stroke of an ic-engine, Measurement Science and Technology 16 (12) (2005) 2437–2445.
- [16] H. Li, G.B. Rieker, X. Liu, J.B. Jeffries, R.K. Hanson, Extension of wavelength-modulation spectroscopy to large modulation depth for diode laser absorption measurements in high-pressure gases, Applied Optics 45 (2006) 1052–1061.
- [17] P. Kluczynski, O. Axner, Theoretical description based on Fourier analysis of wavelength-modulation spectrometry in terms of analytical and background signals, Applied Optics 38 (1999) 5803–5815.
- [18] J. Reid, D. Labrie, Second-harmonic detection with tunable diode lasers – comparison of experiment and theory, Applied Physics B 26 (1981) 203–210.
- [19] L.S. Rothman, D. Jacquemart, A. Barbe, D. Chris Benner, M. Birk, L.R. Brown, M.R. Carleer, C. Chackerian Jr., K. Chance, L.H. Coudert, V. Dana, V.M. Devi, J.-M. Flaud, R.R. Gamache, A. Goldman, J.-M. Hartmann, K.W. Jucks, A.G. Maki, J.-Y. Mandin,

S.T. Massie, J. Orphal, A. Perrin, C.P. Rinsland, M.A.H. Smith, J. Tennyson, R.N. Tolchenov, R.A. Toth, J. Vander Auwera, P. Varanasi, G. Wagner, The HITRAN molecular spectroscopic database and HWAKS (HITRAN atmospheric workstation), *Journal of Quantitative Spectroscopy and Radiative Transfer* 96 (2005) 139–204.

- [20] E.E. Whiting, New empirical approximation to the Voigt profile, *Journal of Quantitative Spectroscopy and Radiative Transfer* 16 (1976) 611–614.
- [21] S.T. Sand, J. Wang, J.B. Jeffries, R.K. Hanson, Diode-laser absorption sensor for line-of-sight gas temperature distributions, *Applied Optics* 40 (2001) 4404–4415.