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In situ H₂O and temperature detection close to burning biomass pellets using calibration-free wavelength modulation spectroscopy

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Abstract. The design and application of an H₂O/temperature sensor based on scanned calibration-free wavelength modulation spectroscopy (CF-WMS) and a single tunable diode laser at 1.4 μm is presented. The sensor probes two H₂O absorption peaks in a single scan and simultaneously retrieves H₂O concentration and temperature by least-squares fitting simulated $1f$ -normalized $2f$ -WMS spectra to measured $2f/1f$ -WMS signals, with temperature, concentration and nonlinear modulation amplitude as fitting parameters. Given a minimum detectable absorbance of $1.7 \times 10^{-5} \text{ cm}^{-1} \text{ Hz}^{-1/2}$, the system is applicable down to an H₂O concentration of 0.1 % at 1000 K and 20 cm path length (200 ppm·m). The temperature in a water-seeded lab-scale reactor (670-1220 K at 4 % H₂O) was determined within an accuracy of 1 % by comparison with the reactor thermocouple. The CF-WMS sensor was applied to real-time in situ measurements of H₂O concentration and temperature time histories (0.25 s time resolution) in the hot gases 2 to 11 mm above biomass pellets during atmospheric combustion in the reactor. Temperatures between 1200 and 1600 K and H₂O concentrations up to 40 % were detected above the biofuels.

1. Introduction

Combustion and gasification of biomass play an increasingly important role in the energy industry [1]. The chemical composition of biomass, in particular chlorine, sulfur and alkali metals, however, evokes ash-related operational problems, such as fouling, corrosion and agglomeration, as well as potentially hazardous emissions [2]. The efforts to understand the underlying chemistry and abate these issues involve investigating the gas-phase reactions of the ash-related species after their release from the solid fuel. While the secondary reactions are rather well understood, more knowledge is needed about the primary reactions, those that occur directly after volatile release, close to the burning fuel [3]. Process gas temperature and concentration of major combustion/gasification species, such as water vapor (H_2O), are important parameters for reliable quantification of the gas-phase compounds, and may serve as input to particle and kinetic models.

Strategies to tackle the above mentioned research questions include thermochemical conversion of single biofuel particles in well controlled and characterized laboratory flames or reactors [4-8]. In such experiments, the combustion process (drying, devolatilization, char combustion) occurs on the order of seconds or minutes (depending on the particle size and oxidizing conditions), during which the particle itself and the surrounding atmosphere will undergo large and fast changes in temperature and composition. A suitable analytical technique to detect volatile species in close proximity to the particles should be able to accurately measure in situ, in real-time (sub-second time resolution), and in a wide dynamic range, preferably without frequent calibration procedures. Robust techniques are required since the measurement may involve the harsh environment of a flame, temperatures up to 1700 K, high soot concentrations and the presence of ash particles.

Optical methods are promising tools to investigate the dynamic behavior of molecular and atomic species in combustion environments [9, 10]. One of the most established optical techniques to meet the requirements identified above is laser-based absorption spectroscopy, in particular tunable diode laser absorption spectroscopy (TDLAS) [11, 12], which is frequently applied in combustion research and industry for thermometry and determination of species concentration [13-15]. The gas temperature can be inferred by probing two or more molecular transitions, whose line strengths exhibit different temperature dependencies [16, 17]. Robust, low-cost two-line thermometry with TDLAS is a viable alternative to thermocouples (TCs) in

harsh and high temperature environments. Line-of-sight (LOS) methods are of advantage when the scope of the investigation includes (potentially pressurized) reactor facilities with limited optical access [14].

The most basic TDLAS approach, direct absorption spectroscopy (DAS), often lacks sufficient sensitivity and baseline stability. Wavelength modulation spectroscopy (WMS) [18] can improve sensitivity and robustness (by noise reduction), but requires calibration procedures for both species and temperature quantification, which can be difficult in practical applications. Recently, several approaches for calibration-free WMS (CF-WMS) have been suggested [19-25], usually based on normalizing ηf -WMS with $I f$ -WMS signals to account for instrumentation factors and a wavelength dependent laser intensity. CF-WMS systems were successfully employed for temperature and concentration measurements in shock-tubes [26], engines [27], scram-jet combustors in the presence of inhomogeneously distributed temperature and species concentration [28], and in coal-fired high pressure combustion facilities [29]. So far, most implementations of CF-WMS used two lasers to probe and analyze transitions in different wavelength regions, and focused on recovering DAS lineshapes for conventional two-line thermometry via the peak values or integrated absorbances of the absorption lineshapes.

Here, we present a compact wavelength-scanned CF-WMS sensor based on a single diode laser that simultaneously obtains temperature and H₂O concentration from a curve fit to a group of H₂O absorption lines using spectroscopic data available from the HITRAN database and literature. The information about the analyte can be extracted based on measurements of (i) the laser intensity without target species absorption (background signal), (ii) the laser intensity with target species absorption (analytical signal including the background), and (iii) the frequency response of the laser to the scan across the group of absorption lines. A laboratory-scale furnace, denoted single pellet reactor (SPR), was used to validate the system performance and to study atmospheric biomass combustion. In a first demonstration of the applicability of the sensor, H₂O concentration and gas temperature above burning biomass pellets were measured as a function of combustion time and height above pellet (HAP).

2. Calibration-free wavelength modulation spectroscopy scheme

The wavelength-scanned CF-WMS scheme presented in this work (Fig. 1) is based on the approach introduced by Sun et al. [24] and extended to spectral lineshape fitting by Goldenstein et al. [25]. This CF-WMS method offers the well documented advantages of (i) being valid at

any modulation amplitude and optical depth (as long as Beer-Lambert's law is valid), (ii) incorporating the actual, measured frequency dependent background signal into the simulated absorption, which avoids the need to model the scanned and modulated laser intensity, and (iii) processing both simulated and measured laser intensities with the same digital lock-in amplifier and low pass filter, which eliminates the need for the Fourier series formalism to simulate the WMS signals, and facilitates multi-harmonic detection [30, 31].

Fig. 1. Flow chart of the CF-WMS scheme. A digital lock-in amplifier with low-pass filter was used to extract the simulated and measured $1f$ - and $2f$ -WMS signals. The frequency response of the laser scan and the background intensity are recorded once before a measurement series.

In WMS, the laser current is varied by both a low frequency scan and a high frequency sinusoidal modulation, so that the frequency of the laser light, $\nu(t)$, is given by

$$\nu(t) = \nu_s(t) + a_m(t) \sin(2\pi f_m t + \theta), \quad (1)$$

where $\nu_s(t)$ is the frequency response of the laser scan, $a_m(t)$ the (nonlinear) modulation amplitude, f_m the modulation frequency, and θ allows for a phase shift between the laser intensity and frequency modulation. Using Beer-Lambert's law, the intensity of the analytical signal after passing the target region can be written as

$$I_A(\nu) = I_{BG}(\nu) e^{-\alpha_A(\nu)}, \quad (2)$$

where $I_{BG}(\nu)$ is the frequency dependent background signal in the absence of the analyte and $\alpha_A(\nu)$ represents the absorbance due to the analyte. The background signal, which includes unwanted frequency dependent losses, such as absorption by other species and etalon effects, is measured separately. In general, the absorbance, $\alpha(\nu)$, due to a target species with relative concentration, c , along the LOS can be described as

$$\alpha(\nu) = cPL \sum_j S(\nu_j, T) \chi(\nu_j, c, P, T), \quad (3)$$

where P is the pressure (atm), L the absorption path length (cm), $S(\nu_j, T)$ the line strength ($\text{cm}^{-2}/\text{atm}$) of the j -th transition at frequency ν_j and temperature T (K), and $\chi(\nu_j, c, P, T)$ is the lineshape function (cm). For a given temperature, the line strength can be calculated using the partition function [32]. The measured background and simulated absorbance, $\alpha_{\text{Sim}}(\nu)$, are combined to yield a simulated laser intensity

$$I_{\text{Sim}}(\nu) = I_{\text{BG}}(\nu) e^{-\alpha_{\text{Sim}}(\nu)}. \quad (4)$$

In the CF-WMS scheme, the simulated and analytical intensities are then both processed by the same digital lock-in amplifier that extracts the WMS signals according to [24]

$$\text{WMS}_{nf/1f} = \frac{\sqrt{\{I[\nu(t)] \sin(2\pi n f_m t)\}^2 + \{I[\nu(t)] \cos(2\pi n f_m t)\}^2}}{\sqrt{\{I[\nu(t)] \sin(2\pi f_m t)\}^2 + \{I[\nu(t)] \cos(2\pi f_m t)\}^2}}. \quad (5)$$

The obtained simulated wavelength-scanned $1f$ -normalized $2f$ -WMS signal is least-squares fitted to the analytical $2f/1f$ -WMS spectrum with the species concentration, the temperature and the nonlinear modulation amplitude as free parameters. Since the laser frequency response to the scan can be nonlinear for some lasers, the modulation amplitude is allowed to change as a function of time (frequency). The phase shift, θ , is obtained from the algorithm prior to the fit by comparison between the simulated and analytical laser intensities. In case the collisional broadening parameters are not well known, the integrated absorbance of the simulated DAS signal can be used as suggested by Goldenstein et al. [25].

In the present work, to realize the described CF-WMS scheme, we employ H_2O transitions previously identified as promising for two-line thermometry [16], together with HITRAN 2012 spectroscopic data [33] and self-broadening temperature dependence coefficients available from the literature [16]. The line parameters are listed in Table 1. Two distinct peaks can be observed in the WMS spectrum. WMS-Peak 1 consists of two, and WMS-Peak 2 of three closely spaced, overlapping H_2O lines. The main contributing lines within each peak have the same lower state energies, which are sufficiently different between the peaks to render them suitable for two-line thermometry. The combined line strengths of peaks 1 and 2 are shown as a function of temperature in Fig. 2a, whereas Fig. 2b presents the peak line strength ratio and the corresponding temperature sensitivity, defined as the peak ratio per unit change in temperature. Although the peak ratio is not used to calculate the temperature in the present CF-

WMS method, it still represents the sensor's sensitivity to temperature changes. At temperatures below 450 K, the temperature sensitivity is high, but the H₂O detectability decreases due to the decreasing peak line strengths. At temperatures above 2600 K, the peak ratio is not particularly sensitive to temperature changes, which makes accurate measurements difficult. Thus, the selected H₂O absorption lines are suitable in the temperature range from 450 to 2600 K. A more detailed characterization of this CF-WMS scheme and a performance evaluation of the sensor up to 2100 K will be given in a separate work.

WMS-Peak	Wavenumber cm ⁻¹	Line strength cm ⁻² /atm	Lower state energy cm ⁻¹	γ -air cm ⁻¹	γ -self cm ⁻¹	n_{air}	n_{self}^*
Peak 1	7153.7207	1.9e-6	2552.88	0.0553	0.371	0.62	0.82
	7153.7484	5.5e-6	2552.86	0.0537	0.371	0.62	0.82
Peak 2	7154.3533	9.3e-5	1789	0.021	0.215	0.57	0.65
	7154.3534	2.8e-4	1789	0.0325	0.333	0.57	0.65
	7154.5950	8.0e-6	2142.6	0.0414	0.281	0.41	0.5

Table 1. Spectroscopic data for the selected H₂O lines from the HITRAN 2012 database. *The temperature dependence coefficient values for γ -self are taken from Ref [16].

Fig. 2. (a) Combined line strengths of the two groups of lines denoted as WMS-Peak 1 and WMS-Peak 2 as a function of temperature. (b) Ratio of the WMS-peak line strengths versus temperature, and temperature sensitivity, given as the peak ratio per unit change in temperature.

3. Experimental setup

3.1 TDLAS sensor

A schematic drawing of the experimental TDLAS setup is shown in Fig. 3a. The setup is based on a fiber-coupled distributed feedback (DFB) laser (Nanoplus) operating around 1398 nm (7153 cm^{-1}) and a low-noise current driver (ILX-Lightwave, LDC-3724-I). An optical fiber splitter (Newport, F-CPL-B12351) and single mode fibers distribute the light to different experimental sites. An uncoated, solid fused silica etalon with a free spectral range of 1.5 GHz (SLS Optics) is used to obtain the frequency response of the laser scan prior to a measurement series. Sensitive and fast photodetectors are used to collect the etalon transmitted (RedWave Labs, D100) and analytical (Thorlabs, PDA20CS) signals. A narrowband optical filter (Thorlabs, FB1400-12) is installed in front of the latter detector to minimize the influence of stray light and background radiation from the combustion process. Synchronized waveform generation (National Instruments, PXI-5402) and data acquisition (National Instruments, PXIe-6356) boards installed in a PC and controlled by LabVIEW are employed to scan and modulate the laser and acquire the photodetector signals (10 averages), respectively. The laser frequency is scanned with a 40 Hz triangular waveform, on which a sinusoidal modulation at 5 kHz with a modulation amplitude of 0.13 cm^{-1} is superimposed to perform WMS.

Fig. 3. (a) Schematic of the experimental TDLAS setup. PD - photodetector, 90/10 - fiber splitter, FGen - function generator, DAQ - data acquisition. Schematic drawing (b) and photograph (c) of the SPR in the upper position.

The selected modulation frequency was the highest for which optimum analog-to-digital conversion of the $2f$ component could be guaranteed with the available maximum data acquisition rate (1.25 MS/s). A higher data acquisition rate would enable higher modulation

frequencies and potentially further noise reduction. The modulation amplitude was chosen to maximize the $2f$ -signal of WMS-Peak 2. The nf -WMS signal extraction and fitting is performed offline using Matlab. A curve fit to a single spectrum usually takes several seconds. For fast, online analysis in monitoring applications, the speed of the fitting procedure could be improved, by, for example, fitting only around the peak center.

3.2 Single pellet reactor

The single pellet reactor (SPR), heated by two electric heating elements in ceramic insulation, is depicted in Figs. 3b and 3c. The pellet is placed in platinum basket on a sample holder, which is connected to a micrometer stage to enable adjustment of the HAP. A pneumatic device moves the reactor between a lower position (sliding hatch closed, sample holder outside reactor) and an upper position (sliding hatch open, sample holder inside reactor), for sample insertion and combustion, respectively. A carrier gas flow can be supplied via a steel wool filled steel cylinder at the bottom of the furnace. A thermocouple located above (sensor validation) or beside (biomass combustion) the steel cylinder measures the temperature in the SPR. Small openings in the front and back plates of the SPR grant optical access to the furnace, which also features a visual inspection window. For the validation measurements, to increase the H_2O concentration in the SPR beyond ambient levels, water was sprayed into the carrier gas flow with the help of a nebulizer (Burgener Research Inc., T2100-760) and a peristaltic pump (Gilson, Minipuls 3). Connected to an analytical balance (the sample holder hanging on the balance), the SPR can also be used as a macro thermogravimetric analyzer (macro-TGA) to record the pellet weight loss during the combustion process. The SPR was previously employed to study effects of pelletizing conditions and raw material properties on combustion behavior [5, 8].

3.3 Biomass characteristics

Two different, pelletized fuels of relevance for the energy industry were used in the present study, one softwood derived fuel consisting of whole trees (stems) with bark, denoted energy wood (EW), and a fuel containing agricultural residues, called wheat straw (WS). These fuel types differ in chemical composition with respect to ash content as well as form and relative content of major ash forming elements K, Ca, Mg, P, S, Si and Cl. The moisture content of EW and WS, determined by standard wet chemical analysis (Bioenergy2020 laboratories, Graz, Austria), was 6.4 % and 10 %, respectively, while the (chemical bound) hydrogen content was about 6 % for both fuels. The pellets were of cylindrical shape with diameters 8 mm and 6 mm, and lengths 16 mm and 8 mm for EW and WS, respectively. The initial weights of the pellets

used in the combustion experiments were 835 ± 5 mg for EW and 245 ± 5 mg for WS. Pelletized biomass was chosen to simulate realistic combustion conditions, although the larger particle size complicates the interpretation of the results as physical properties of the pellets (e.g. size, heating rate, radial temperature gradient and chemical composition) change during combustion.

4. Sensor validation and evaluation

The temperature sensor performance was validated by measuring in the H₂O-seeded SPR in the range 670 to 1220 K. For these measurements, the thermocouple was situated in the gas flow above the steel cylinder and close to the laser beam (as shown in Fig. 3b). The carrier gas was nitrogen, and the flow rate was 6 liter/min to ensure optimal operation of the nebulizer. The reactor was in the lower position to guarantee that the gases mixed well and yielded a homogenous temperature and water vapor distribution. The length of the SPR chamber along the beam, and thus the absorption path length, was 20 cm. A low flow of nitrogen was introduced at the beam entrance and exit openings of the reactor to confine the hot water vapor to the SPR and to prevent ambient H₂O entering the chamber. For comparison with the $2f/1f$ -WMS data, DAS spectra were also recorded, and evaluated using the integrated absorbance.

Typical DAS and CF-WMS signals obtained in the validation experiments are displayed in Figs. 4a and 4b, respectively. Experimental raw data (black circular markers) and least squares fits (red solid lines) of simulated spectra to the raw data are presented. The individual DAS lineshapes (blue solid lines) in panel (a) are shifted along the y-axis for clarity. The residuals of the curve fits are shown below each spectrum. From Fig. 4b, the minimum detectable H₂O absorbance (3σ) for the $2f/1f$ -WMS signal is $1.7 \times 10^{-5} \text{ cm}^{-1} \text{ Hz}^{-1/2}$, which yields a detection limit for H₂O of 0.1 % at 1000 K and 20 cm path length, or 200 ppm·m.

The accuracy of the CF-WMS temperature sensor was examined by measuring the temperature in the SPR in steps of 50 K. As shown in Fig. 5, the CF-WMS method achieves an agreement with the TC reading to within 10 K (mean accuracy of 0.8 %). The mean H₂O concentrations measured in the water-seeded SPR were 4.0 ± 0.6 % and 5.1 ± 0.7 % for CF-WMS and DAS, respectively. The large standard deviation was due to random H₂O fluctuations in the seeding system. An absolute validation with known H₂O concentration was not possible in these experimental settings, as the amount of H₂O seeded into the SPR could not be quantified with sufficient accuracy.

An additional weak line at 7153.64 cm^{-1} of unknown origin was observed. This peak had to be accounted for in the DAS fits, where the results depended on an accurate determination of the peak area, but was less important (and thus not accounted for) in CF-WMS, as the H_2O /temperature assessment depended on the overall fit, and was little influenced by a minor deviation far from the line center. The reason for the less accurate DAS temperature determination and the systematically higher H_2O concentration measured with DAS can probably be attributed to difficulties to accurately determine the integrated absorption in the presence of low-frequency baseline noise and drift.

Fig. 4. (a) Typical DAS signal of the selected H_2O transitions recorded during the SPR validation measurements, with individual DAS lineshapes shown as blue solid lines. (b) Corresponding $2f/1f$ -WMS signal. (c) Typical $2f/1f$ -WMS signal obtained in the biomass combustion experiments, and

corresponding background signal (green dashed line). Raw data (black circular markers) and best fits (red solid lines) are presented, together with fit residuals shown below each spectrum.

Fig 5. CF-WMS (red square markers) and DAS (blue circular markers) measured temperature in the water-seeded SPR compared to the SPR thermocouple reading. The relative error of the CF-WMS data is shown below.

5. Single biomass pellet combustion experiments

Single biofuel pellets were combusted in the SPR at a set temperature of 1123 K and an ambient air carrier gas flow rate of 4 liter/min (to ensure a laminar flow and flame). During the combustion process, H_2O and temperature were measured in situ at four different HAPs with an acquisition time of 0.25 s. The absorption path length was determined by comparing the flame size to the known dimensions of sample basket and steel cylinder on photographs of the burning pellets taken through the visual inspection window of the SPR. The optical path lengths were determined to be 3.4 cm and 2.1 cm for EW and WS, respectively.

Figure 4c shows a typical $2f/1f$ -WMS signal (black circular markers) obtained during biomass conversion and the corresponding background signal (green dashed line). The major part of the background signal arose from H_2O in the ambient air carrier gas that was heated upon entering the SPR. Since the ambient H_2O in the SPR had a different temperature and concentration compared to the water vapor in the biomass flame, the displayed $2f/1f$ -WMS signal represents inhomogeneous conditions. However, since the measured background signal was included in the simulated absorption, information about the H_2O in the flame could be extracted. This would also hold if a part of the background would originate from ambient H_2O at room temperature, which was not the case for the specific absorption lines chosen in this work. The good fit to the

measured $2f/1f$ -WMS signal suggests that H_2O and temperature were rather homogeneously distributed in the flame. The somewhat larger residual in Fig. 4c, as compared to the residual in Fig. 4b, could imply slightly inhomogeneous conditions in the flame or dissimilar background signals in the absence and presence of the flame.

Fig. 6. Typical time histories of temperature (a) and H_2O concentration (b) measured 2, 4, 7 and 11 mm above EW pellets combusted in the SPR. Flow and TC temperature (a) and weight loss data (b) are shown for comparison. The grey area depicts the flaming devolatilization phase.

Figures 6 and 7 present temperature (panel a) and H_2O concentration (panel b) measured at HAPs of 2, 4, 7 and 11 mm for EW and WS pellets, respectively (every second data point is displayed). The start of the measurement (time zero) occurs a few seconds after sample introduction to the furnace, due to the time it takes to lift the SPR to its upper position and place the pellet below the laser beam. The grey area indicates the flaming devolatilization phase (from onset to extinction of the flame), which for particles of the size used also includes heating and drying. Representative weight loss curves (green dashed lines) for the pellets are shown in panels (b). As expected, most of the weight is lost during devolatilization and a change in slope occurs at the beginning of the char combustion phase. The combustion process is longer for EW than for WS due to the higher EW pellet weight. It should be noted that not the entire char combustion phase is displayed, as no further temperature and H_2O changes occurred after 210 and 90 seconds for EW and WS, respectively. The repeatability of the measurements was

examined by recording 4 consecutive EW time histories at HAP 2 mm, which were almost identical.

In Figs. 6a and 7a, the set temperature of the SPR (open square markers) and the actual temperature of the carrier gas flow (solid circular markers) around the pellet are indicated. Since the carrier gas flow was introduced to the SPR in a stainless steel tube close to the reactor heating elements, its temperature was higher than the reading of the TC, which, in the pellet experiments, was located in the center lower part of the furnace to avoid being influenced by the flame. The actual flow temperature was estimated from the TC reading after lowering the SPR furnace to its closed position. The temperature of the gases in the furnace then equilibrated, leading to an instantaneous rise of the TC reading to about 1170 K.

Fig. 7. Typical time histories of temperature (a) and H_2O concentration (b) measured 2, 4, 7 and 11 mm above WS pellets combusted in the SPR. Flow and TC temperature (a) and weight loss data (b) are shown for comparison. The grey area depicts the flaming devolatilization phase.

The temperature time histories shown in Figs. 6a and 7a are similar both between the fuels and at the different HAPs. The initial sharp peak is probably due to the developing flame passing the laser beam. Then, the temperature decreases as the laser probes a lower part of the flame, or even below the flame, which is likely for EW (large flame) at a HAP of 2 mm. The temperature then increases as particle and flame shrink, and the laser beam again probes the

combustion zone. As expected, this effect is less pronounced the higher the HAP and for WS due to the smaller particle size. In the char combustion phase, the temperature above the pellet decreases almost to the carrier gas flow temperature, but is still slightly higher because of the heat released by the glowing pellet. The released H_2O originates mostly from the fuel moisture. The measured H_2O concentration time histories displayed in Figs. 6b and 7b are similar for the two fuels, and vary only slightly with HAP. The reason for this may be that the released H_2O did not participate in gas-phase reactions over the investigated range of HAPs. In general, the measured gas temperatures and moisture evaporation behavior agree well with single biomass particle combustion simulations [34].

The total amount of H_2O released from the pellet was estimated from the integrated H_2O concentration time history using the ideal gas law and assuming a homogeneous water and temperature distribution in the entire flame. The total measured amount of released H_2O was found to be a factor of 2.4 higher than the initial moisture content in EW pellets, whereas it was a factor of 1.3 higher for WS. Additional H_2O may have been produced by combustion reactions of chemically bound hydrogen. This is supported by the fact that for EW pellets somewhat more water was observed with increasing HAP, where more oxygen is available due to diffusion from the carrier flow. The pellets could also have absorbed moisture from ambient air during storage in the laboratory. On the other hand, farther away from the pellet, a part of the water may have already diffused from the flame. Also, an initial loss of moisture from the pellet surface during sample insertion into hot SPR, prior to the start of the measurement, cannot be excluded. Further, systematic investigations are needed to better characterize the biomass flame and understand volatile release during combustion.

6. Conclusions

Accurate real-time data on temperature and H_2O concentration in combustion environments are desirable for both fundamental research and industrial monitoring. In this work, we present and demonstrate a TDLAS sensor based on a single DFB-laser and CF-WMS that accurately retrieves path-averaged H_2O /temperature information from hot gases without calibration. Assuming that the spectroscopic data of the measured H_2O transitions are well known, concentration, gas temperature and (nonlinear) modulation amplitude can be obtained by recording the laser scan frequency response and the modulated laser intensities with and without analyte. The described scanned-wavelength CF-WMS scheme, where simulated I/f -normalized

2*f*-WMS spectra of a group of lines are least-squares fitted to measured 2*f*/*1f*-WMS signals, can readily be applied to detection of other species.

The operation of the compact and robust sensor is demonstrated in a water-seeded laboratory-scale furnace and above burning biomass particles in the temperature range 470 to 1600 K, in the presence of ~0.1 to 40 % water vapor, and at absorption path lengths between 2 and 20 cm. The sensor is well suited for in situ H₂O/temperature detection in close proximity to biomass particles during thermochemical conversion. Given that atomic and molecular absorption line strengths depend on temperature, the sensor will aid accurate TDLAS-based quantification of relevant compounds in combustion and gasification research, such as alkali metals, which, in turn, will facilitate investigation of ash-chemistry in biomass combustion processes.

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