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J. M. Seitzman, R. Tamma and B. T. Scully
Georgia Institute of Technology
Atlanta, GA

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BROADBAND INFRARED SENSOR FOR ACTIVE CONTROL OF HIGH PRESSURE COMBUSTORS

J. M. Seitzman,* R. Tamma† and B. T. Scully†

Aerospace Combustion Laboratory
Georgia Institute of Technology
School of Aerospace Engineering
Atlanta, GA 30332-0150

Abstract

A sensor approach for monitoring water mole fraction and temperature uniformity in the exit plane of a high pressure gas turbine combustor is presented. The sensor, intended for use in an active control system, is based on infrared line-of-sight absorption measurements of water with a relatively broadband light source. Performance of the sensor was simulated using a computer model based on the HITRAN/HITEMP database for the infrared absorption of water. Specific regions of interest near 2.5 μm were identified, based on their relative sensitivity to temperature. One region is relatively insensitive to temperature and permits monitoring of integrated water mole fraction across the exhaust. Two wavelengths, one with positive slope sensitivity and the other negative, are used to monitor the uniformity of the exhaust temperature profile. The linearity and sensitivity of the approach to uncertainties in the spectral shape and width, and the wavelength of the filtered light source are also presented.

Introduction

For improved efficiency, aircraft turbine engine designs call for progressively higher compressor pressure ratios. Simultaneously, there is growing interest in control strategies for optimizing engine performance across a range of operating conditions, e.g., takeoff, cruise and high altitude combustor relight. These control systems are intended to improve performance of turbine engine combustors in a variety of areas, including pollutant emissions and combustion efficiency. Additionally, the high stresses and high temperatures that turbine blades encounter require maintenance of optimum turbine inlet conditions. For example, sufficiently uniform temperature profiles may be necessary to ensure that excessively hot pockets of gas do not impinge on the turbine blades. Likewise at high stress regions near the blade roots, sufficiently cold gases may be needed to prevent blade damage. The need for active control is especially important as engines become smaller and are obliged to achieve optimal performance in off-design conditions and under the course of normal engine wear.

While active control of jet engine combustors offers great potential for such improvements, it requires sensors that are capable of monitoring performance parameters in high temperature and high pressure gases. In such a hostile environment, optical techniques are a natural solution, as they offer the possibility of non-intrusive measurements. In particular, line-of-sight absorption based on infrared (IR) diode lasers has shown particular promise.[1-2] In general, the IR or near-IR lasers interact with rotational-vibrational transitions of a molecule. Strategies for simultaneous determination of gas concentration and temperature have been developed[3] and utilized for control of simple combustion devices.[4]

Current laser-based approaches have been limited, however, by the small wavelength range accessible by available laser sources. Single lasers can be tuned over small spectral regions, thus appropriate sensors may involve a number of laser sources. Also, laser sources are not always available in regions that coincide with desired absorption features of the molecules of interest. Furthermore, the need for spectrally narrow laser sources is diminished at high pressures. Since diode lasers generally have a spectral output that is much narrower than the spectral lines of molecules, they are able to resolve single absorption

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* Assistant Professor, Member AIAA

† Graduate Research Assistants

lines. At high pressures, however, the molecular absorption features broaden to an extent that individual lines begin to disappear, the wings of one line overlap neighboring lines. Thus at elevated pressures, absorption sensors based on spectrally broader light sources have been suggested.[5]

In this paper, we present a sensor strategy for monitoring conditions at the exit plane of a high pressure gas turbine combustor. The strategy is based on a spectrally broad, but potentially tunable, light source and line-of-sight absorption measurements of water. Specifically, we consider approaches for monitoring 1) water mole fraction, as a measure of overall combustor health, and 2) temperature uniformity at the exit of turbine blade. Water was chosen from among the other likely candidates, i.e., CO_2 and CO because of its strong absorption features and because spectral regions exist with negligible gas absorption interferences from other important species.

Absorption Model

In order to simulate the performance of the absorption sensor, the infrared absorption features of water were modeled using a standard approach. First, the spectral absorption coefficient k_ν [e.g., cm^{-1}] for a gas mixture at given thermodynamic conditions, including composition, is given by

$$k_\nu = \frac{p}{kT}\sum_i \chi_i \sum_j S_{ij}(T)\phi_{ij}\left(\nu-\nu_{ij},T,p,\chi_i\right) \quad (1)$$

where k is Boltzmann's constant, p and T are the gas pressure and temperature at the point, χ_i is the mole fraction of the ith gas species with an absorption transition centered at frequency ν_{ij} having a line strength $S_{ij}(T)$ [e.g., $\text{cm}^{-1}/(\text{molec cm}^{-2})$] and line shape function $\phi_{ij}(\nu,T,p,\chi_i)$ [e.g., cm]. The summations in Eq. (1) represent the contributions from multiple transitions (j) and absorbing species (i).

For a low intensity light source with total intensity $I_{o,total}$, the overall absorbance through a nonuniform gas mixture of length L is then given by

$$\begin{aligned} Absorbance &= 1-\int_{-\infty}^{\infty} I_\nu(L)d\nu \Big/ I_{o,total} \\ &= 1-\int_{-\infty}^{\infty} g(\nu)\exp\left[\int_0^L -k_\nu(x)dx\right]d\nu \end{aligned} \quad (2)$$

where $I_\nu(L)$ is the spectral intensity at frequency ν after propagation from the light source (at x=0) to L, $k_\nu(x)$ is the spectral absorption coefficient at a distance x from the source, and $g(\nu)$ is the normalized spectral distribution of the light source defined by $g(\nu) = I_\nu(x=0)/I_{o,total}$.

For the modeling presented here, the line strength information was obtained from the HITEMP database, a high temperature version of the HITRAN96[6] database for selected molecules, in conjunction with the HAWKS computer software.[7] The spectral line shapes were assumed to be Voigt functions,[8] a combination of Doppler broadening and collision broadening. While collisional narrowing and line shifts are likely to occur at high pressures,[9-10] such effects have been neglected in these calculations. Since these effects are typically much less than the nominal value of the collisional broadening, they should not be important for the current simulations, which assume a light source much broader than the spectral width of the absorption features. The collisional broadening information was also obtained from HITEMP.

Equations (1) and (2) show that the overall absorbance of the gas generally depends on the composition, temperature and pressure of the gas, through $k_\nu(x)$. Thus with appropriate selection of measurement frequencies, it is possible to monitor these variables. As the gas transmittance is integrated over the path length L, however, any resulting measurement must be recognized as some path averaged property. In addition, the measured values will depend (through the functional form of $k_\nu(x)$) on the combined distributions *of all the properties* over the path. For example, a temperature inverted from an absorption measurement will typically be different than a mass-averaged temperature across the path due to the nonlinear dependence of Eq. (1) on temperature.

When accurate, spatially resolved measurements are required in nonuniform flows, this path averaging may represent a significant problem and call for complex reconstruction algorithms.[11] The measurement requirements of a sensor used for active control can, however, be less demanding. For example, a reasonable estimate of the average value of water mole fraction or temperature at the combustor exit may be sufficient to monitor the health of the combustor.

Exhaust Conditions and Band Selection

In order to identify a sensor strategy for water measurements in the exhaust plane of a gas turbine combustor, the following conditions were considered. Across the exit, local gas temperatures were assumed to be within the range 700-2000 K. A nominal pressure of 10 atm, constant across the exhaust, was used. Pressures in excess of 5 atm and the temperature range given are reasonable values for aircraft engines with pressure ratios above 12-15 at a range of altitudes and operating conditions. Additionally, the exhaust composition assumes comparable water and carbon dioxide mole fractions, which is appropriate for jet fuels with C:H ratios near 1:2.

For the purposes of this simulation, the sensor was assumed to integrate over a 10 cm path length. Additionally, the sensor's light source/detector system was assumed to be able to achieve a Lorentzian profile with a resolution (full-width at half maximum, FWHM) of 10 cm^{-1}. The Lorentzian profile, with its extensive wings, was chosen to simulate a light source that employs a spectral bandpass filter with moderate, but finite, out-of-band rejection.

Table 1. Principal vibrational bands for water absorption in the 3000-8000 cm^{-1} range. In each frequency region, the band with the largest peak absorption is denoted the primary band.

Region cm^{-1} (μm)	Primary Band	Other Important Bands
3000-4000 (2.5-3.3)	(0,0,1)-(0,0,0) or ν_3	(1,0,0)-(0,0,0) (0,2,0)-(0,0,0) (0,1,1)-(0,1,0) (1,1,0)-(0,1,0) (0,3,0)-(0,1,0) (0,2,1)-(0,2,0)
4800-5800 (1.7-2.1)	(0,1,1)-(0,0,0) or $\nu_2+\nu_3$	(1,1,0)-(0,0,0) (0,3,0)-(0,0,0)
6800-7600 (1.3-1.5)	(1,0,1)-(0,0,0) or $\nu_1+\nu_3$	(0,2,1)-(0,0,0) (2,0,0)-(0,0,0) (0,0,2)-(0,0,0) (0,3,1)-(0,1,0) (1,1,1)-(0,1,0) (2,1,0)-(0,1,0)

For reasons related to thermal background emission, detector performance and absorption in optical materials, we restrict our consideration to wavelengths less than about 3 μm, or frequencies greater than ~3300 cm^{-1}. In this range, the absorption features of water can be divided into three distinct regions.

Table 1 lists the most significant water vibrational transitions for each of the three regions. In the first, roughly 3000-4000 cm^{-1}, the dominant features result from two fundamental transitions, specifically transitions from the ground level to two excited vibrational levels, (1,0,0) and (0,0,1). In the other two regions, 4800-5800 and 6800-7600 cm^{-1}, combination bands primarily contribute to peak absorption levels about one order of magnitude weaker than in the fundamental bands. It is in the shortest wavelength region (~1.3-1.5 μm) that most diode-laser measurements of water have been conducted.[2-4,10,12-14]

For the conditions at the combustor exhaust, all three regions offer potential for broadband water sensing. From the standpoint of interferences due to absorption by other major gas constituents, primarily CO_2, most of the ~7000 cm^{-1} band is virtually problem free. Regions of the other bands can also be found with little or no CO_2 interference.[5] For example, the region above ~3800 cm^{-1} is free of CO_2 interference. Strong absorbances, which provide better measurements from a signal-to-noise perspective, are more easily found in the strongly absorbing 3000-4000 cm^{-1} region. However, absorbances above 1% can also be found for the other regions.

Finally, it is important to find spectral regions with low absorbance for background/baseline corrections. For sensors that must operate in real or dirty environments, the possibility of scattering particles or degradation of optics must be considered. This requires the ability to record the transmitted light intensity in spectral regions with little or no gas absorption. Because these background sources of light extinction are not uniform over large wavelength ranges, the regions of low absorption should be as close to the measurement wavelength as possible. It is this last constraint, along with the lack of CO_2 interferences, that led us to focus currently on the region above 3800 cm^{-1}. The other water absorption bands, however, also hold promise for sensors based on the approaches described below.

Results

Spectral absorption coefficients were calculated according to Eq. (1). The summation over spectral lines was performed for all transitions with center frequencies within 16 cm^{-1} of the desired frequency. This is at least 40 times greater than the half-width of the transitions at the conditions of interest, and calculations with greater summation ranges yield effectively identical results.

Figure 1 illustrates the effect high pressures on the absorption coefficients of water. As suggested above, the collision broadening of individual transitions at 10 atm causes them to merge, and recognizable absorption features actually consist of multiple absorption lines. This becomes even more pronounced at higher operating pressures. While a light source with a relatively narrow spectral output is needed to resolve single absorption features at 1 atm, a much broader source can be used at higher pressures. At high pressures, the extensive broadening also makes it more difficult to find regions between lines that have sufficiently low absorption for correcting background absorption. Figure 2 shows the spectral absorption coefficients in a region around 4000 cm^{-1} at 10 atm, and at 700 and 2000 K, the limits of the temperature range considered here. The noticeable change in k_ν with temperature in different regions on either side of ~4000 cm^{-1} holds good promise for temperature sensing.

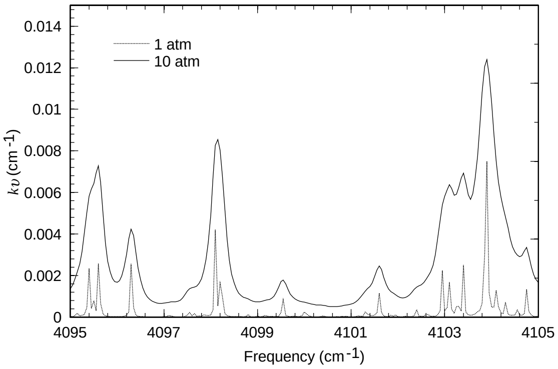

Figure 1. Spectral absorption coefficient k_ν for a mixture containing 5% water by mole at 1300 K in a region above 3800 cm^{-1} for two pressures, 1 and 10 atm.

These high pressure spectral absorption coefficients were then used to calculate overall absorbances for a 10 cm^{-1} bandwidth light source over a path length of 10 cm and a water mole fraction of 0.05, according to Eq. (2). The integration over frequency was carried out over a range ten times greater than the FWHM of the light source; larger integration ranges did not yield significantly different results.

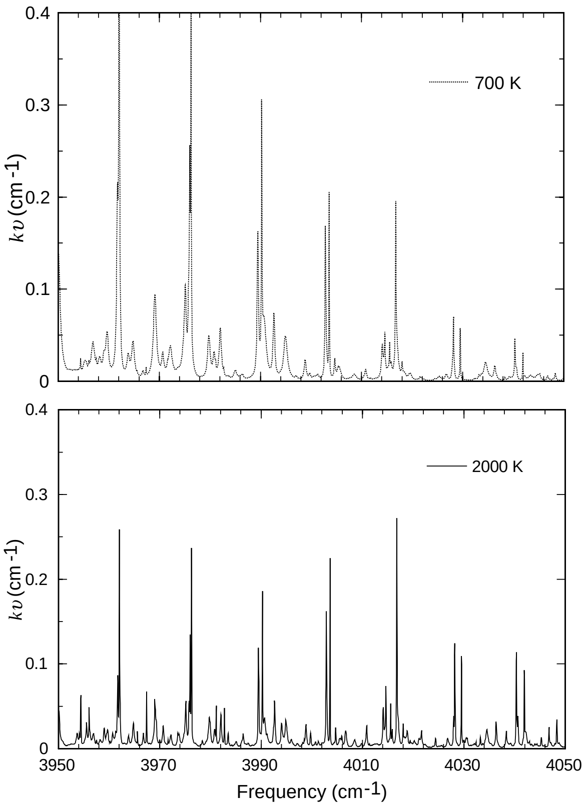

Figure 2. Spectral absorption coefficient k_ν for 5% water at 700 K and 2000 K, and a pressure of 10 atm in a region near 4000 cm^{-1} that shows strong temperature dependence.

Figure 3 shows the overall absorbances for the three temperatures over a broader frequency range of 3800-4200 cm^{-1}. We note that over most of this range, the absorbances are above 1%, ensuring reasonable signal-to-noise ratio measurements. In the region beyond 4300 cm^{-1}, the absorbance falls below 0.2% for temperatures below 1600 K. Thus, background corrections, e.g., for scattering, could be made there. Figure 3 also shows that the broadband absorbance has a noticeably different temperature dependence in three regions. At lower frequencies, nearer 3800 cm^{-1}, the absorbance decreases with increasing temperature, while above 4100 cm^{-1}, the absorbance increases. In a central region, near 4000 cm^{-1}, the temperature dependence of the absorbance is greatly reduced.

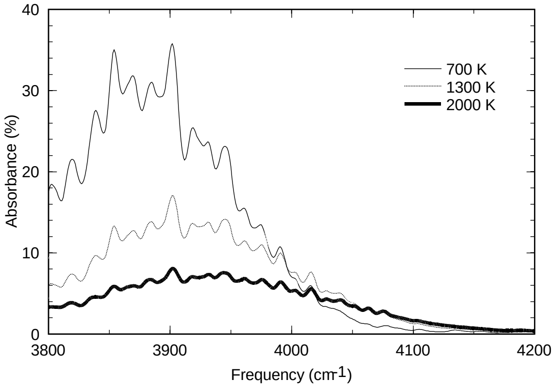

Figure 3. Overall absorbance for a broadband (10 cm^{-1} Lorentzian) light source over a 5 cm path length in a uniform gas mixture at 10 atm, consisting of 5% H_2O by mole.

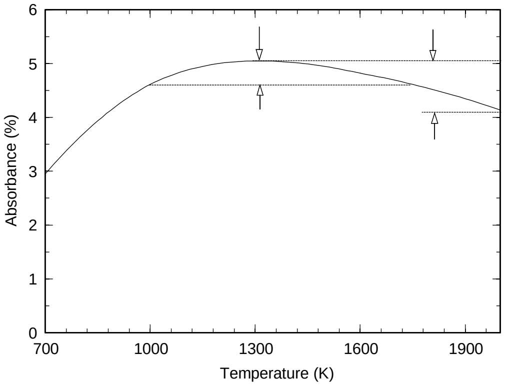

Figure 4. Temperature (in)sensitivity of the broadband absorbance for the conditions shown in Fig. 3 and a light source centered at 4038 cm^{-1}.

Sensing Mole Fraction

Our first goal was to monitor water mole fraction in the gases at the combustor exhaust. Recall that the calculated absorbances shown in Fig. 3 are based on a constant mole fraction of water. Thus if the absorbances in the central region of the figure were completely independent of temperature, an absorption measurement there would yield the true, integrated water mole fraction over the path.

Figure 4 shows the temperature dependence of the absorbance for a light source centered at 4038 cm^{-1}. Compared to other frequencies, a light source centered here has about the smallest relative change in absorbance (±25%) over the whole temperature range considered here, 700-2000 K. For higher temperature conditions, the temperature independence improves. For example, a sensor using this center frequency would have a ±5% relative change in absorbance over a temperature range of 1000-1700 K, and ±11% for 1000-2000K. Thus integrated water fraction measurements could be made to a ±5% relative accuracy under these conditions. A sensor with this accuracy should be adequate for use in an active control system monitoring overall combustor health. It would also be necessary to know the pressure along the absorption path, which is nearly constant and could be measured by standard sensors at a wall.

Because the absorption at this temperature insensitive location is not too strong, we also find that the linearity of the absorbance with respect to water mole fraction is good. Figure 5 shows the variation in absorbance with water level, for a constant temperature of 1300 K. The absorbance deviates from a best-fit linear dependence on mole fraction by no more than 10% for levels up to 0.065. The fact that we can accurately approximate the exponential dependence in Eq. (2) with a linear function should allow a sensor/active control system to employ simpler data reduction procedures.

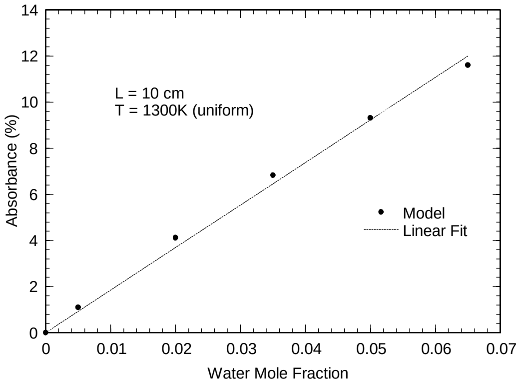

Figure 5. Variation in absorbance with water mole fraction for a 10 cm^{-1} bandwidth light source centered at 4038 cm^{-1} for uniform combustor exhaust conditions of 10 atm, 1300 K, and a 10 cm path length. The line is a best-fit to the calculated absorbances.

We also investigated the sensitivity of the water measurements to potential uncertainties in exact center frequency of the light source and its spectral distribution. We compared the predicted absorbances of a sensor using the nominal values stated above to absorbances produced using up to a ±2 cm^{-1} shift in the center frequency combined with variations in the widths of the distribution of ±3 cm^{-1} (±30% in FWHM). With these effects combined, the relative change in absorbance was less than 6.8%. We also tested a change in the distribution from a Lorentzian to a Gaussian. The Gaussian, which has wings that decay much faster than the Lorentzian, produced a relative change in absorbance of about 10%. Thus the measurement is not overly sensitive to the wings of the light source.

Sensing Temperature Uniformity

Our second goal was to find an approach for sensing the uniformity of the temperature profile at the combustor exhaust (or turbine inlet). This can be accomplished with absorption measurements in the other two regions shown in Fig. 3. Based on the higher absorbance for cold water compared to hot water near 3800 cm^{-1}, absorption measurements in this region will be more heavily weighted towards portions of the flow containing cold water. A temperature measurement based on the absorbance here would tend to be lower than the actual mass-averaged temperature across the path if regions containing cold water were present. Similarly, measurements near 4150 cm^{-1} are more sensitive to parts of the exhaust that contain hot water and would over predict the average temperature. Thus a comparison of the temperatures predicted by the two measurements would be a test of a flow's temperature uniformity.

One method for inferring temperature from the absorbance measurements requires a value for the integrated water mole fraction, which could be obtained from a measurement at 4038 cm^{-1}. Given this water level, the measured absorbance can be inverted to a temperature using a relationship derived from data such as that expressed in Fig. 3. Two locations of interest are 3810 cm^{-1} and 4100 cm^{-1}. Both have reasonable absorption levels and both show a monotonic response to temperatures from 700 K to nearly 2000 K.

Water/Temperature Correlation

So far we have based our calculations, such as those shown in Figs. 3-5, on independent values for water mole fraction and temperature. For a combustor exhaust, this is unrealistic; there should be some correlation between water content and temperature. For instance, high temperature regions will tend to consist of hot combustion products, including high water content, that have not mixed with much of the colder, drier dilution air from the compressor.

In order to investigate the importance of such a relationship, we used a simple linear correlation. First, we assumed that the gas at any point in the combustor exhaust was composed of mixtures of stoichiometric combustion products and dilution air. The adiabatic flame temperature of a stoichiometric mixture of jet fuel burning with preheated air was taken to be roughly 2500 K, and the products would contain roughly 13% water. For the nominal conditions of the dilution air, we assumed a temperature of 700 K and 0.5% water. At both these extremes, the molecular weight of the gas is nearly identical. For any intermediate mixture, we assume a linear relation between temperature and water content. Essentially, this requires constant specific heats, complete combustion, and no heat losses. While none of these assumptions is completely valid, they should be sufficient to test the behavior of the proposed sensor approach in a nonuniform combustor exhaust.

The effect of the water/temperature correlation on the absorbance measurements is evident in Fig. 6. It shows the overall absorbances for the same conditions used in Fig. 3. Now, absorption measurements are weighted more towards hot gases. Specifically, the region near 4100 cm^{-1} shows a much greater sensitivity to hot gases, i.e., an increased absorbance. In addition, the very large increase in absorbance for the coldest gases is somewhat reduced, but still evident near 3800 cm^{-1}.

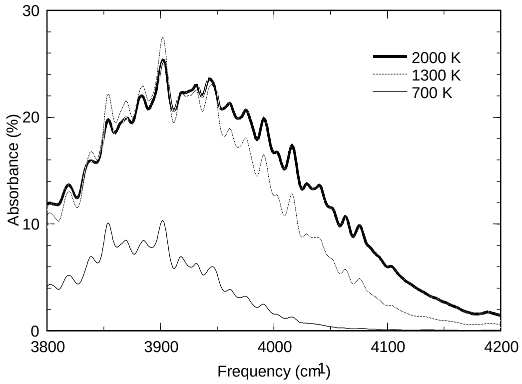

Figure 6. Overall absorbance for a broadband (10 cm^{-1} Lorentzian) light source over a 10 cm path length in a uniform gas mixture at 10 atm and various temperatures. The water content at each temperature varies linearly with temperature.

Simulated Sensor Performance

In order to simulate the performance of the sensor for monitoring integrated water mole fraction and temperature uniformity in a combustor exhaust, we calculated the overall absorbances that would be obtained for various exhaust gas profiles. In each, the temperature range is limited to 700-2000 K, based on a reasonable assumption that at the combustor exhaust pure dilution air may be present, but that some mixing of the combustion products would have occurred.

All the profiles shown in Fig. 7 have the same overall water content (4.67%) and same mass-averaged temperature (1300 K). The profiles include: 1) a single stream (Uniform); 2) a bimodal distribution with two partially mixed conditions (Partial Mixing); 3) a bimodal distribution with a mixed stream and small regions of pure dilution air that might be needed to protect a casing, hub or blade root (Cooling Layer); and two trimodal distributions with a small region of poor mixing containing either very 4) hot (Hot Spike) or 5) cold (Cold Spike) gases.

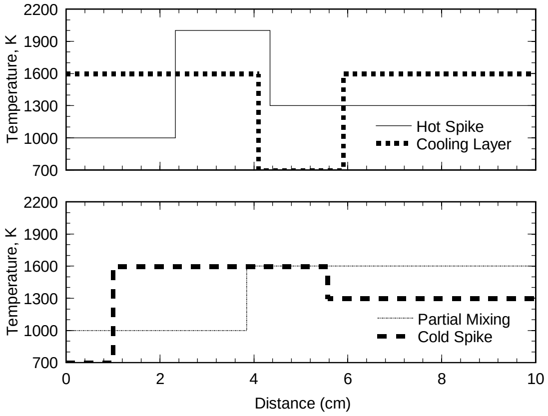

Figure 7. Profiles of temperature and water mole fraction across a 10 cm path through the exit plane of a combustor used to test sensor performance.

Table 2 contains the calculated absorbances for each of the above profiles at a temperature insensitive frequency. The calculated absorbances are all rounded to the nearest 0.001 to simulate a resolution of 10^{-3} absorbance for a practical sensor. Also shown are the mole fractions that would be inferred from the rounded absorbances, based on the linear fit of Fig. 5. For the uniform profile, the inferred mole fraction is 0.048, which is about 2.7% above the expected value of 0.0467. The error results from the small nonlinearity of the absorbance with mole fraction. Compared to the uniform profile, only the two profiles that contain pure dilution air (Cooling Layer and Cold Spike) produce larger errors in integrated water fraction. This results from the increased temperature sensitivity at the extreme low temperature region (see Fig. 4). Though even for the Cooling Layer, which has nearly one-fifth of its length at 700 K, the error is under 10%.

Table 2. Calculated absorbance values for the gas profiles shown in Fig. 7 at a pressure of 10 atm that simulate a sensor with a 10 cm^{-1} wide Lorentzian light source centered at 4038 cm^{-1}.

Profile	Absorbance	Integrated Mole Fraction	% Error from Uniform
Uniform	0.088	0.048	–
Partial Mixing	0.091	0.049	2.1
Cooling Layer	0.098	0.053	9.4
Hot Spike	0.089	0.048	0
Cold Spike	0.094	0.051	6.3

Table 3 lists the absorbance values at the two temperature sensitive positions noted in the previous section. For the various profiles, the change in absorbance at both frequencies, compared to the uniform distribution, is well above the 0.001 resolution assumed for a practical sensor. For some profiles like the Partial Mixing and Cold Spike cases, both frequencies would record a significant difference from the Uniform case. For the Hot Spike profile, only the measurement sensitive to hot gases records a change. This is the advantage of choosing two frequencies with opposite dependence on temperature, at least one should notice excursions from the average.

Since there would not necessarily be prior knowledge of the average gas temperature, we can not compare the absorbances to an (unknown) uniform case to infer temperature uniformity. There are a number of methods to convert the measured absorbances to temperature estimates. The first method, described above, uses the calculated variation of absorbance with temperature for a uniform path having the same (known) integrated mole fraction. The results of this method are shown in the left side of Table 4. For the Uniform case, both temperatures have a small error (10 K) from the expected value of 1300 K. This is associated with rounding the calculated absorbance values to the nearest 0.001. Thus the estimated sensor resolution gives around a 10-20 K temperature resolution at this condition.

As expected, there is a noticeable difference between the temperatures inferred from two measurement locations for the nonuniform profiles, and for this approach of inferring temperature, the hot measurement is more sensitive to temperature nonuniformities. Cold gases contain little water and supply even less of the absorption at this frequency, so even small deviations from uniform mixing are easily noticed. This is so pronounced that, in the case containing the most 700 K gas (Cooling Layer), the absorbance across the profile is greater than the maximum absorbance possible (the absorbance at 4100 cm^{-1} peaks between 1900 and 2000 K).

Table 3. Absorbances calculated for the profiles of Fig. 7 that simulate a sensor with a 10 cm^{-1} wide Lorentzian light source centered at two temperature-dependent center frequencies with absorbances weighted towards cold (3810 cm^{-1}) and hot (4100 cm^{-1}) gases.

Profile	Absorbance at 3810 cm^{-1} "cold"	Absorbance at 4100 cm^{-1} "hot"
Uniform	0.102	0.023
Partial Mixing	0.097	0.028
Cooling Layer	0.098	0.033
Hot Spike	0.103	0.028
Cold Spike	0.100	0.029

The results for the cold position (3810 cm^{-1}) are also interesting. Even though this position is weighted towards cold gases, none of the inferred temperatures here are less than the mass-averaged value across the path, and all are within 60 K of the true value. It appears that the assumed linear correlation between mole fraction and temperature, and the path lengths of different temperatures needed to maintain a constant mass-averaged temperature across the path roughly cancel the temperature dependence of the absorbance. This suggests that the 3810 cm^{-1} measurements may be able to provide estimates of the average temperature at the exhaust, even in the presence of nonuniform exit profiles.

We also investigated a second method for inferring temperatures from the absorbance values that does not rely on integrated mole fraction measurements. Instead, this method uses the temperature dependence of the absorbance based on the assumed linear correlation between water and temperature. In this case, an absorbance value at a given frequency corresponds to a single combination of temperature and water fraction. The temperature values based on this method are also listed in Table 4. Now we find that the temperatures inferred from the cold frequency measurements are below the average, while they are above the average for the hot case. Also, both sensor positions are now sensitive to temperature nonuniformities. The cold position is, however, better able to sense the difference between profiles. For example, the Partial Mixing, Hot and Cold Spike profiles produce the same result at the hot position, but different temperatures for the cold measurement.

Table 4. Temperatures inferred from the absorbance measurements listed in Table 3 based on two approaches: based on the known integrated water level and from the assumed correlation between water level and temperature. In one case, no temperature can be inferred (NA).

Profile	T (K) from known χ_{H_2O}		T (K) from correlation	
	3810 cm^{-1} "cold"	4100 cm^{-1} "hot"	3810 cm^{-1} "cold"	4100 cm^{-1} "hot"
Uniform	1310	1290	1290	1300
Partial Mixing	1360	1580	1140	1410
Cooling Layer	1350	NA	1150	1500
Hot Spike	1300	1580	1320	1410
Cold Spike	1330	1680	1170	1410

Conclusions

The infrared absorption spectra of the exhaust gases of a turbine engine combustor were modeled in order to simulate the behavior of a sensor for monitoring water mole fraction and temperature uniformity in the combustor exhaust plane. It is intended that this line-of-sight absorption sensor would be employed in an active control system. Unlike most sensors previously proposed, the current approach would employ broadband IR sources, or perhaps a single source with a tunable bandpass filter.

Both path integrated water content and temperature uniformity across the combustor exhaust can be monitored by a sensor using as few as three measurements between ~3800 and 4100 cm^{-1} (~2.63 to 2.38 μm). In this region, the absorption is dominated by water, with little interference from the other gases that comprise the bulk of the combustor exhaust. In addition, interferences associated with "dirty" optics and particle extinction can be assessed at nearby wavelengths that have little water absorption. At the wavelengths chosen, expected absorbance values are between 0.02 and 0.1 for the conditions tested.

Overall water content in the exhaust is monitored at a wavelength with an absorbance that weakly depends on temperature. Based on the simulations, water measurements in a uniform mixture, inferred from a simple linear relation between mole fraction and absorbance, and uncorrected for temperature dependence would have a accuracy (relative) of ~10% over a broad range of temperatures (1000-1700 K) and water levels. Based on background absorption measurements near 4300 cm^{-1} and an estimate of 10^{-3} in absorbance for the resolution of the sensor, mole fraction results would have a 1-2% relative resolution. In the presence of various exhaust profiles, the water monitoring approach also achieved a relative accuracy better than 10%. However, uncertainties in the spectral output of the IR source (center frequency, FWHM, and wing effects) could increase these values slightly. For a sensor in an active control system, the accuracy of this approach should be sufficient for many applications monitoring combustor health. An example would be a control system monitoring changes in water content to assess gross changes in combustor efficiency.

Approaches for monitoring temperature uniformity were also demonstrated and involved comparison of measurements at two wavelengths, one sensitive to cold gases (3810 cm^{-1}) and the other sensitive to hot gases (4100 cm^{-1}). The difference in the temperatures inferred from these measurements is a measure of the temperature uniformity. According to the simulation results, a sensor based on this approach should be easily able to identify nonuniform exhaust profile and even provide a measure of the amount of deviation from a uniform profile. The sensor may even be able to discriminate profiles containing excessive amounts of unmixed hot gases from those with more pronounced cold excursions. In addition, there is evidence that one approach may provide reasonable measures of the path-averaged temperatures, even across nonuniform flows.

The sensor approach described here is not limited to the three frequencies chosen in this work. If there are inaccuracies or missing transitions in the HITEMP data base, there should still be some regions that behave like those used here. Also for changes in expected operating conditions, e.g., pressure and average temperature, we should expect other center frequencies to have better sensitivity than the current choices. Thus, an engine sensor required to operate over a very large range of temperatures, pressures and fuel/air ratios would either require many light sources or a broadly tunable IR source or filter.

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References

[1] Miller, J.H., Elreedy, S., Ahvazi, B., Woldu, F. and Hassanzadeh, P., "Tunable Diode-Laser Measurements of Carbon Monoxide Concentration and Temperature in a Laminar Methane-Air Diffusion Flame," Applied Optics **32**, 6082-6089, 1993.

[2] Arroyo, M.P., and Hanson, R.K., "Absorption Measurement of Water Vapor Concentration, Temperature and Line-Shape Parameters using a Tunable InGaAsP Diode Laser," Applied Optics **32**, 6104-6116, 1993.

[3] Allen, M.G., Davis, S.J., Kessler, W.J., Palombo, D.A. and Sonnenfroh D.M., "Diode Laser Instrumentation for Aeropropulsion Applications," paper AIAA-95-0427, 33rd Aerospace Sciences Meeting, Reno, NV, January 9-12, 1995.

[4] Furlong, E.R., Baer, D.S. and Hanson, R.K., "Combustion Control using a Multiplexed Diode-Laser Sensor," paper AIAA-96-0756, 34th Aerospace Sciences Meeting, Reno, NV, January 15-18, 1996.

[5] Seitzman, J. M., Tamma, R. and Vijayan, R., "Infrafred Absorption Based Sensor Approaches for High Pressure Combustion," paper AIAA-97-0318, 35th Aerospace Sciences Meeting, Reno, NV, January 6-10, 1997.

[6] Rothman, L.S., Gamache, R.R., Tipping, R.H., Rinsland, C.P., Smith, M.A.H., Benner, D.C., Devi, V.M., Flaud, J.-M., Camy-Peyret, C., Perrin, A., Goldman, A., Massie, S.T., Brown, L.R. and Toth, R.A., "The HITRAN Molecular Database: Editions of 1991 and 1992," Jour. Quant. Spectrosc. and Rad. Transfer **48**, 469, 1992.

[7] Rothman, L.S., "HAWKS: HITRAN Atmospheric Workstation," Phillips Laboratory, Geophysics Directorate, 1996.

[8] Sobelman, I.I., Vainshtein, L.A. and Yukov, E.A., *Excitation of Atoms and Broadening of Spectral Lines*," Springer-Verlag, Berlin, 1981.

[9] Varghese, P.L. and Hanson, R.K., “Collisoinal Narrowing Effects on Spectral Lineshapes Measured at High Resolution,” Applied Optics **23**, 2376-2385, (1984).

[10] Nagali, V., Baer, D.S. and Hanson, R.K., “Measurements of H_2O in High-Pressure Flows using Near-IR Diode-Laser Absorption,” paper AIAA-96-0846, 34th Aerospace Sciences Meeting, Reno, NV, January 15-18, 1996.

[11] Kessler, W.J., Allen, M.G., Lo, E.Y. and Miller, M.F., “Tomographic Reconstruction of Air Temperature and Density Profiles using Tunable Diode Laser Absorption Measurements on O_2,” paper AIAA-95-1953, 26th AIAA Plasmadynamics and Laser Conference, San Diego, CA, June 19-22, 1995.

[12] Arroyo, M.P., Birbeck. T.P., Baer, D.S. and Hanson, R.K., “Dual Diode-Laser Fiber-Optic Diagnostic for Water-Vapor Measurements,” Optics Letters **19**, 1091-1093, 1994.

[13] Baer, D.S., Hanson, R.K., Newfield, M.E. and Gopaul, N.K.J.M., “Multiplexed Diode-Laser Sensor System for Simultaneous H_2O, O_2 and Temperature Measurements,” Optics Letters **19**, 1900-1902, 1994.

[14] Baer, D.S., Nagali, V., Furlong, E.R., Hanson, R.K. and Newfield, M.E., “Scanned- and Fixed-Wavelength Absorption Diagnostics for Combustion Measurements using a Multiplexed Diode-Laser Sensor System,” paper AIAA-96-0426, 33rd Aerospace Sciences Meeting, Reno, NV, January 9-12, 1995.