Joint Temperature-Volume Fraction Statistics of Soot in Turbulent Non-Premixed Jet Flames of Ethylene and a JP-8 Surrogate

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Colloquium Turbulent Flames

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Figure 1	(55+ 10) × 2.2 × 2+ 18 =	304
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Figure 4	(50 + 10) × 2.2 × 2 + 53 =	317
Figure 5	(60 + 10) × 2.2 × 2 + 44 =	352
Figure 6	(30 + 10) × 2.2 × 2 + 37 =	213
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Abstract

Soot emissions from internal combustion engines and aviation gas turbine engines face increasingly stringent regulation, but few datasets are available for model development and validation in turbulent, sooting flames, in part due to the difficulty of making quantitative space- and time-resolved measurements in this type of flame. To help address this deficiency, we report here on simultaneous measurement of soot concentration and soot temperature in well-controlled sooting, non-premixed jet flames fueled by ethylene or a prevaporized JP-8 surrogate with a fuel exit Reynolds number of 20,000. The probe volume for the measurements was defined using small, uncooled alumina refractory probes with a 10 mm probe end separation. 2-color pyrometry was used to measure soot temperature, with calibration provided by a high-temperature blackbody source. Extinction of a 633 nm HeNe laser beam was used to determine soot volume fraction. Data were collected along the flame centerline at many different heights and radial traverses were performed at selected heights. A data sampling rate of 5 kHz was used to resolve the turbulent motion of the soot. The results for the ethylene flame show a mean soot volume fraction of 0.4 ppm at mid-height of the flame, with a mean temperature of 1450 K. At greater heights in the flame, the soot intermittency increases and its mean concentration decreases while its mean temperature increases. In the JP-8 surrogate flame, the soot concentration reaches a mean value

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of 1.3 ppm at mid-height of the flame, but the mean soot temperature is only 1270 K. Elevated soot concentrations persist for a range of heights in the JP-8 flame, with a rise in mean temperature to 1360 K, before both soot volume fraction and temperature decrease at the top of this smoking flame.

Keywords: turbulent flame; soot; temperature; ethylene; JP-8

1. Introduction

The deleterious health effects of fine particulate matter (PM) in ambient air have become increasingly evident. These particles penetrate lung tissue and have been shown to effect the pulmonary and cardiovascular systems, leading to increased morbidity and mortality [1,2]. As a consequence, soot emissions from internal combustion engines and aviation gas turbine engines have faced increasingly stringent regulation.

To address these concerns, there is a strong desire among engine designers to have a truly predictive modeling capability for soot formation and emission, one that can properly account for the influence of changes in fuel composition, ambient conditions, and engine design and operation. At this time, such a capability is still lacking. One reason for the lack of predictive models of soot formation in the complex engine combustion environment is the lack of robust, spatially and temporally resolved data in turbulent reacting flow fields, specifically for sooting fuels. Such datasets have been in development for many years for soot-free flames [3] and more recently for a slightly sooting methane flame [4], but available experimental datasets for moderately sooting turbulent flames are largely lacking. Such datasets are needed because under moderately sooting flame conditions, believed to be representative of aviation gas turbine combustors, the soot that is formed radiates energy away from the hottest soot-containing regions to the walls and to the cooler soot-containing regions, thus redistributing the reaction enthalpy and influencing the flame chemistry and burning rate in a coupled manner [5]. The ability of computational models to accurately describe these coupled turbulence/chemistry/soot formation/radiation interactions cannot be tested with data from soot-free or lightly sooting flames.

Unfortunately, many of the laser diagnostic techniques that have been used to provide quantitative space- and time-resolved measurements of flow and scalars in soot-free flames fail or are much more difficult to perform quantitatively in moderately sooty flames. This is largely because these techniques rely on the use of high power, pulsed laser beams, which excite both broadband fluorescence from polycyclic aromatic hydrocarbons (PAH) [5], whose presence is associated with soot formation, and laser-induced incandescence (LII) of the soot itself, which produces a strong background signal throughout visible and near-IR wavelengths [6,7]. Even if such strong background signals can be managed, for application of a particular laser diagnostic, the presence of significant quantities of soot in the flame results in laser beam attenuation as well as laser diagnostic signal attenuation that varies in intensity in both space and time in turbulent flames, making time-resolved quantitative measurements of scalar properties nearly impossible. In fact, even the popular LII technique for measuring soot concentrations suffers from laser attenuation and signal trapping effects that cannot be effectively corrected for on a shot-to-shot basis in turbulent flames. In addition, LII measurements are subject to intensified camera flat field issues [8] and spatio-temporal laser pulse profile difficulties [9] that have been previously discussed in the literature. Temperature measurements in turbulent sooty flames have traditionally relied on coherent anti-Stokes Raman spectroscopy (CARS), but this diagnostic relies on a probe volume defined by overlapping laser beams at a finite angle, resulting in probe volumes that have a complicated shape and which are at least 2 mm in length [10,11]. In addition, the CARS technique suffers from significant non-resonant susceptibility in flames with significant concentrations of ethylene or higher hydrocarbons [11,12] and gives skewed results when probing heterogeneous probe volumes [13], making accurate quantification of temperature in such flames difficult.

In this paper we describe the application of a laser diagnostic technique that actually requires a significant amount of soot loading to generate sufficient signal-to-noise and which simultaneously measures the soot concentration and soot temperature, with high temporal resolution. Thus, joint soot temperature-volume fraction statistics are measured, which is a critical aspect of determining the radiant flux in turbulent, sooty flames [14,15]. This so-called '3-line' diagnostic approach applies laser beam attenuation and 2-color pyrometry, two line-of-sight measurements. To define and to limit the length of the optical probe volume, physical probes are used, which must be designed carefully to avoid unduly perturbing the sampled flame. Coppale and Joyeux [16] previously applied this technique to two turbulent ethylene non-premixed jet flames, but this data is of limited value to modelers because the flames investigated were only lightly turbulent (fuel tube Re of 5700 and 11,800), the fuel delivery tube was of unspecified length (meaning there is no knowledge of the gas velocity profile exiting the tube), and no air coflow was supplied (meaning the external flow boundary conditions are ambiguous). Our measurements build upon this pioneering dataset and apply this technique to fully turbulent flames fueled by both ethylene, a commonly used fuel in soot studies, and a JP-8 surrogate, representative of the flame chemistry and sooting tendency of aviation fuels.

2. Experimental Methods

2.1 Turbulent non-premixed flames

The measurements reported here were performed in two canonical piloted turbulent non-premixed jet flames that have been the focus of a number of measurements at Sandia: an ethylene jet flame and a prevaporized JP-8 surrogate jet flame, both with a jet-exit Reynolds number of 20,000 [17]. The burner design and experimental operation have been specifically tailored to allow meaningful comparisons with CFD models [17]. The ethylene flame is stabilized on a fuel tube with an ID of 3.2 mm, whereas the prevaporized JP-8 surrogate, composed of m-xylene and n-dodecane (23:77 by liquid volume), is stabilized on a fuel tube with an ID of 2.5 mm. Further details concerning the burner design and operation are available in ref. 17. The ethylene flame does not show any apparent emission of soot in the exhaust (i.e., it is non-smoking), whereas the JP-8 surrogate flame is a lightly smoking flame.

2.2 '3-line' soot diagnostic

Figure 1 shows a schematic of the '3-line' soot diagnostic that was implemented. Laser attenuation was performed with a 632.8 nm HeNe laser, so that soot dimensionless extinction coefficients previously measured at this wavelength could be utilized to interpret the measurement. A reference laser intensity measurement was made using a beamsplitter and a photodiode detector with a 632.8 nm laser line filter (3 nm FWHM). After passing through the flame probe volume, the laser beam was separated from the 2-color soot emission signals with the use of a dichroic beamsplitter. The transmitted beam was collected in a 12-inch (30.5-cm) diameter integrating sphere, before passing through a laser line filter onto a photodiode detector, in order to remove any influence from turbulent flame beam steering on the attenuation measurement.

The soot emission signals were split with a cube beamsplitter and then passed through bandpass filters with center wavelengths of 850 nm and 1000 nm before passing onto thermoelectrically cooled silicon avalanche photodiode (APD) detectors. Calibration of the two-color pyrometry diagnostic was performed using a high-temperature blackbody source with a mirror that redirected the blackbody light to the avalanche photodiode detectors.

A key aspect of the 3-line diagnostic technique is the need to insert a two-ended probe into the flame to limit the length of the optical interrogation region. In previous studies, these probes have typically been constructed of water-cooled steel or aluminum tubing, in some cases with insulation wrapped around the outside of the probes. With this design approach, the probe tubes are necessarily quite large and also provide a thick thermal quench layer. To minimize probe perturbation of the flow field and flame sheets, we adopted the approach first used by Sivathanu and Faeth [18], with tapered, or, in our case, step-reduced, refractory probe ends that are uncooled. Figure 2 shows photographs of the cooled housings containing the outer probe ends and the uncooled probe tips that enter the flame. These probe tips have an OD of 0.25 in. (6.35 mm) and an ID of 0.175 in. (4.45 mm). A small flow of nitrogen (< 1 slpm) was introduced into each probe end to reduce the likelihood of soot deposition within the tubes.

Early testing of the alumina probes revealed that they transmitted radiant emission from the broader flame through the probe walls to the pyrometry detectors at measurable levels. Therefore, the outer surfaces of the probes were painted black with high-temperature paint, which corrected this problem. In addition, a small amount of radiation was transmitted to the detectors from the hot tips of the probes when they were located in the hottest regions of the flames, leading to a non-zero radiant background signal. This background signal, which showed up as a baseline shift on the time records, was subtracted before processing the datasets to determine the soot radiant temperature.

2.3 Data collection and processing

Data were collected along the flame centerline at many different heights and radial traverses were performed at selected heights. A data sampling rate of 5 kHz was used to resolve the turbulent motion of the soot. Digital time records were collected as 40 sets of 5000 data points (i.e. a 1 sec time record) at a given location in the flame before a computer-controlled X-Y-Z translation stage moved the flame to the next programmed sampling position. A 10 mm probe end separation was used for most of the measurements, but some data were also collected for probe separations of 5 mm and 20 mm. The soot extinction measurement was converted to soot volume fraction according to the Beer-Lambert law with a dimensionless extinction coefficient, Ke, of 9.3, as determined in laminar flames by Williams et al. [19]. The optical path length of soot extinction was assumed to be equal to 2 mm less than the probe tip separation, to account for the effect of the small purge flow out the tips of the probe.

2.4 Measurement uncertainty

As previously demonstrated, the predominant source of uncertainty in measurements of soot volume fraction and soot temperature using the 3-line technique is due to uncertainties in the optical properties of soot [20]. Uncertainty in the dimensionless extinction coefficient at 632.8 nm dominates the uncertainty in the derived soot volume fraction, while uncertainty in the spectral variation of the absorptivity between 850 nm and 1000 nm (assumed here to follow a $1/\lambda$ dependence between these two wavelengths) dominates the uncertainty in the derived soot temperature. Based on our previously reported analysis [20], the uncertainty in soot volume fraction is estimated as ± 12%, in those regions where there is measurable laser beam attenuation, and the uncertainty in soot temperature is estimated as ± 3%.

In addition to these 'static' measures of experimental uncertainty with the 3-line diagnostic, in a turbulent flame there are additional uncertainties associated with variations in soot temperature across the optical probe volume [21], as well as variations in the soot optical properties in space and time in the flame. These additional uncertainties will increase the uncertainty in results derived from a given temporal record, but should have a minor influence on the uncertainty in the average data collected from the flame, except in locations where soot is undergoing active inception, where its optical properties are rapidly evolving.

3. Results and Discussion

3.1 Ethylene flame

Figure 3 shows typical temporal records for laser transmittance and soot emission along the flame centerline of the ethylene jet flame. At both lower and upper heights, there are distinct time intervals when no soot signals are apparent in the probe volume. To ensure that the deduced soot temperature data are not influenced by low signal-to-noise emission data at times when there is little to no soot in the probe volume, cut-off criteria for minimum emission signals were established at each sampling location, based on the emission signal levels when the laser transmission measurement shows no soot in the probe volume. The emission signals show better sensitivity to low soot concentrations than the laser attenuation measurement. However, since 2-color pyrometry relies on the ratio of the emission signals, it is very sensitive to noise and a conservative minimum signal cutoff criteria has been chosen to reduce the probability of distorted derived soot temperatures in low signal regions.

Figure 5 shows the corresponding computed soot volume fraction and soot temperature time records for the raw data shown in the top of Fig. 3. From this time record, it appears that the mean volume fraction is approximately 0.5 ppm, with occasional dropouts (i.e. moments with no soot) and instantaneous peak volume fractions of just over 1 ppm. The soot temperature at this location appears to be approximately 1500 K, with excursions down to 1200 K and up to just over 1800 K. Of course, it should be appreciated that because this measurement occurs over a path length of 10 mm in the flame, it is likely that soot at different temperatures is being sampled and the 2-color pyrometry measurement is inherently biased towards the hotter soot that is present in the probe volume [21].

Figure 6 shows the measured probability distribution functions (pdf) for soot concentration and soot temperature at mid-height and at an elevated height of the ethylene flame. Fig. 7 shows the corresponding joint pdfs (i.e. bivariate histograms). The results show a mean soot volume fraction of 0.4 ppm at mid-height of the ethylene flame, with a mean temperature of 1450 K. At any given instant, the soot volume fraction typically falls between 0.1 and 0.7 ppm with a temperature between 1300 and 1650 K. At greater heights in the flame, the soot intermittency increases, its mean concentration decreases, and its mean temperature increases. As is apparent in Figs. 6 and 7, however, occasionally higher local concentrations of soot are seen at greater heights in the flame. Furthermore, lower concentrations of soot are sometimes associated with lower temperatures, which could reflect the occurrence of soot-containing quenched vortices [20].

Coppalle and Joyeux [16] reported a maximum soot volume fraction of 1.9 ppm along the centerline of their jet flame with Re = 11,800. However, they assumed a dimensionless extinction coefficient of only 3.4. Correcting this to the K_e value of 9.3 used here, their maximum volume fraction becomes 0.69 ppm, which is just a little higher than the values measured here in a more turbulent ethylene flame. The soot temperature pdfs they measured are similar to those shown in Fig. 5, with the exception that their deduced temperatures are higher by nearly 100 K. Lee et al. [11] report a peak soot volume fraction of 1 ppm for an ethylene jet flame with Re = 19,100. Correcting for the difference in dimensionless extinction coefficient (they assumed $K_e = 4.5$), their measurement corresponds to a peak f_v of 0.5, in good agreement with that measured here.

3.2 JP-8 surrogate flame

Corresponding results from the prevaporized JP-8 surrogate flame are shown in Figs. 8-9. In the JP-8 surrogate flame, the soot concentration reaches a mean value of 1.3 ppm at mid-height of the flame, but the mean soot temperature is only 1270 K. Elevated soot concentrations persist for a range of heights in the JP-8 flame, with a rise in mean temperature to 1360 K, before both soot volume fraction and temperature tail off at the top of this smoking flame. The probability distribution function shapes for soot volume fraction and temperature are similar for the JP-8 surrogate flame compared to the ethylene flame, except that the temperature distribution for the JP-8 flame at intermediate heights shows evidence of a small peak towards higher temperatures riding on the shoulder of the main peak. The joint pdfs also are similar to those observed for the ethylene flame, except for the evidence of the small higher temperature 'arm' that is present at intermediate heights, as well as the lack of increase in temperature of the most probable soot measurement with increasing measurement height.

The soot volume fraction-temperature joint pdfs measured in these turbulent jet flames are qualitatively similar to those previously reported along the centerline of a 2-m diameter JP-8 pool fire, with an increasing spread of both volume fraction and temperature as one proceeds up the flame [20]. In fact, the joint pdf at mid-height of the JP-8 surrogate jet flame (z/d = 150) is nearly identical (even in quantitative values) to the joint pdf measured at mid-height of the JP-8 pool fire (z/d = 0.5).

4. Conclusions

Soot concentration (volume fraction) and temperature have been measured in turbulent non-premixed jet flames fueled by undiluted ethylene and prevaporized JP-8 surrogate, respectively, using the combined laser extinction/2-color emission pyrometry approach over an optical pathlength of 10 mm. Both the mean soot concentration values and the statistical distributions show approximately twice the soot concentrations in the JP-8 surrogate flame as in the ethylene flame. Further, the soot in the JP-8 surrogate flame is approximately 200 K cooler than the soot in the ethylene flame. For both flames, the distribution of soot concentrations and temperatures widens with increasing flame height, even as the fraction of time in which no soot is present in the probe volume increases. This data should aid in the development and validation of non-premixed turbulent flame simulations that include soot formation and radiation.

Acknowledgments

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Figure Captions

Figure 1. Schematic of diagnostic configuration used to perform 3-line measurements of soot temperature/concentration statistics in the turbulent jet flames.

Figure 2. Optical probe for performing 3-line measurements of soot temperature/ concentration statistics in the turbulent jet flame. Aluminum optical housing (left) is water-cooled and provides N_2 purge gas. Refractory probe ends (right) are uncooled.

Figure 3. Sample time record of laser transmittance and soot emission along the centerline of the ethylene jet flame for a height of 44.8 cm (z/d = 140), top, and for a height of 64.0 cm (z/d = 200), bottom. Note that the emission signals are recorded as negative values (i.e. increasing signal corresponds to larger negative numbers).

Figure 4. Sample time record of deduced soot volume fraction and soot temperature for a height of 44.8 cm (z/d = 140) along the centerline of the ethylene jet flame. The volume fraction is shown in red, corresponding to the left axis, and the soot temperature is in black and corresponds to the right axis.

Figure 5. Soot volume fraction pdf (left) and soot temperature pdf (right) along the centerline of the ethylene jet flame. Top of the figure is for a height of 44.8 cm (z/d = 140) and bottom is for a height of 64.0 cm (z/d = 200).

Figure 6. Joint pdfs of soot volume fraction and soot temperature at a height of 44.8 cm (z/d = 140) (left) and at a height of 64.0 cm (z/d = 200) along the centerline of the ethylene jet flame.

Figure 7. Soot volume fraction pdf (left) and soot temperature pdf (right) along the centerline of the JP-8 surrogate jet flame. Top of the figure is for a height of 37.5 cm (z/d = 150) and bottom is for a height of 68.75cm (z/d = 275).

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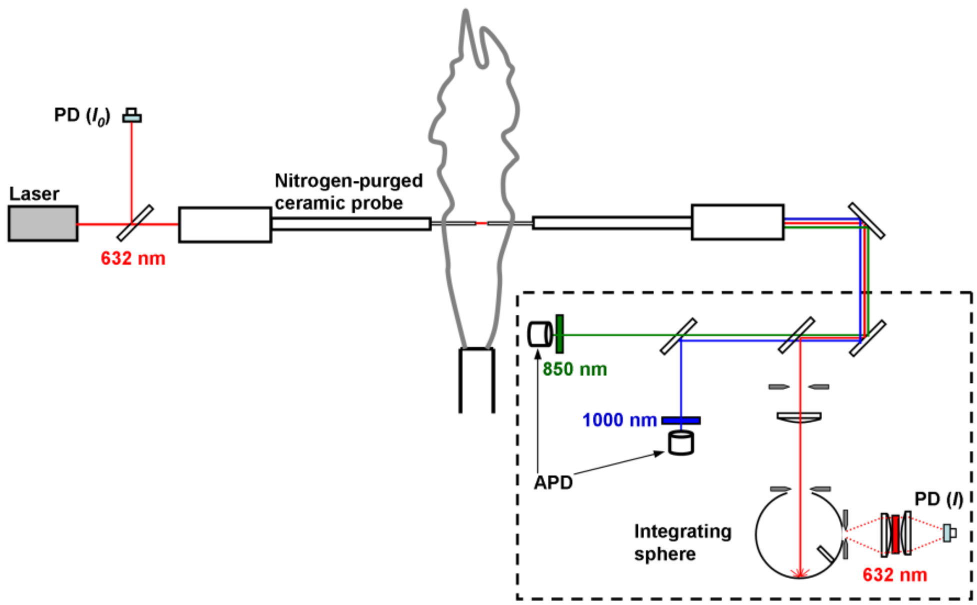

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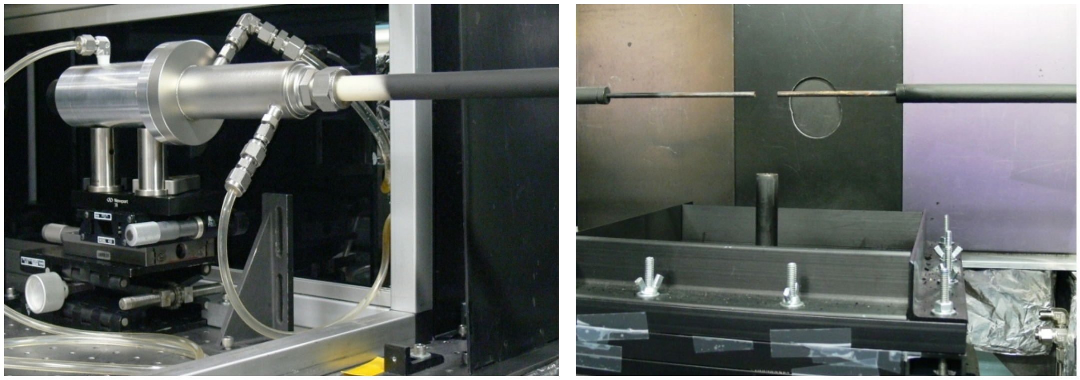

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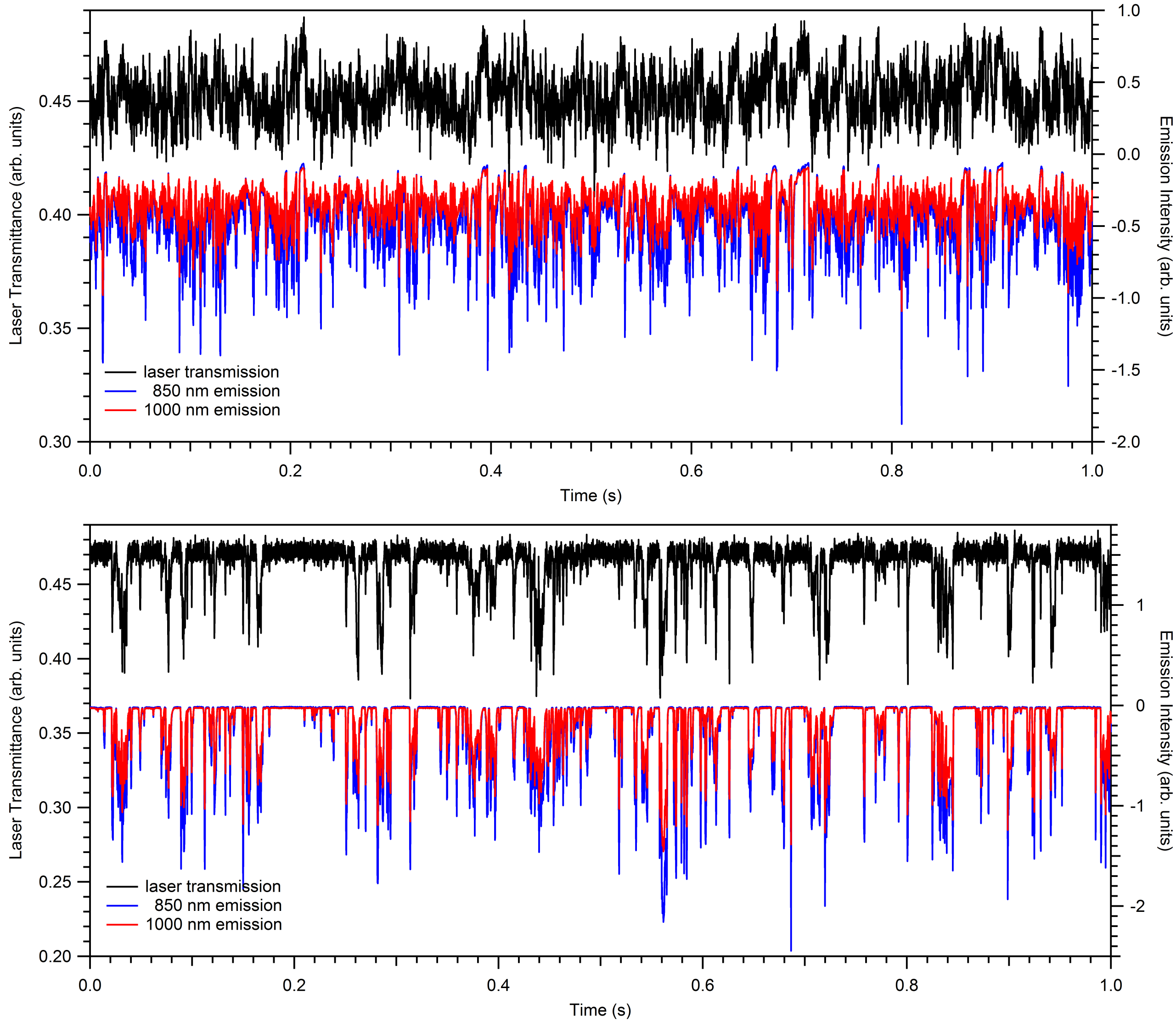

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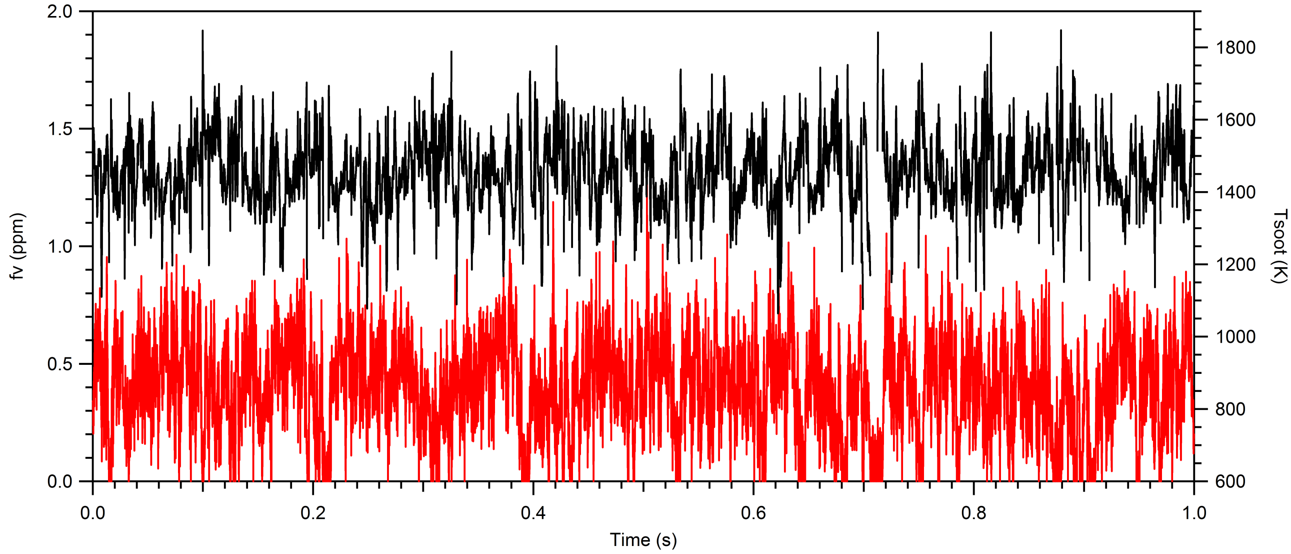

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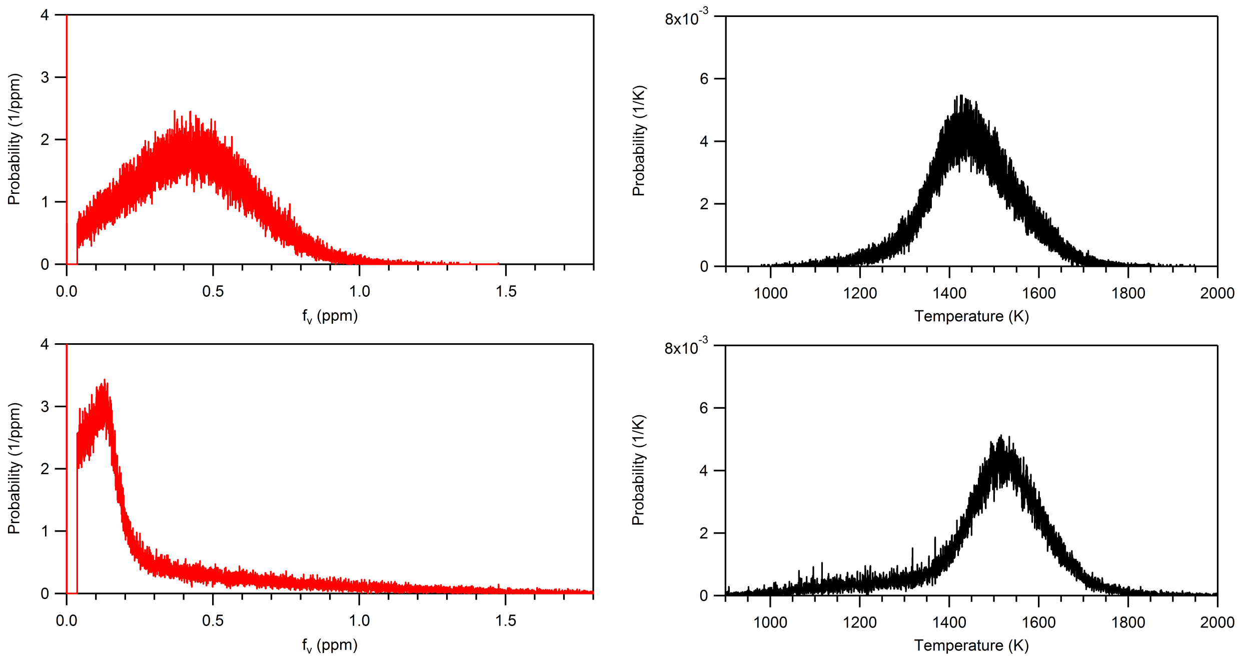

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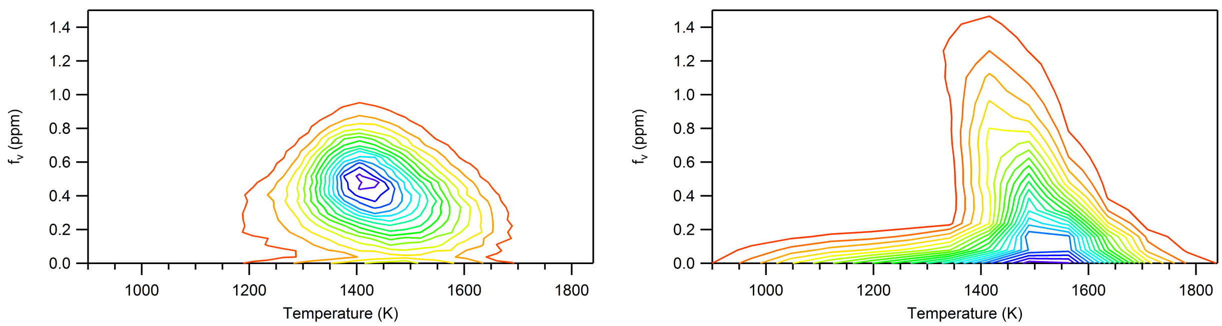

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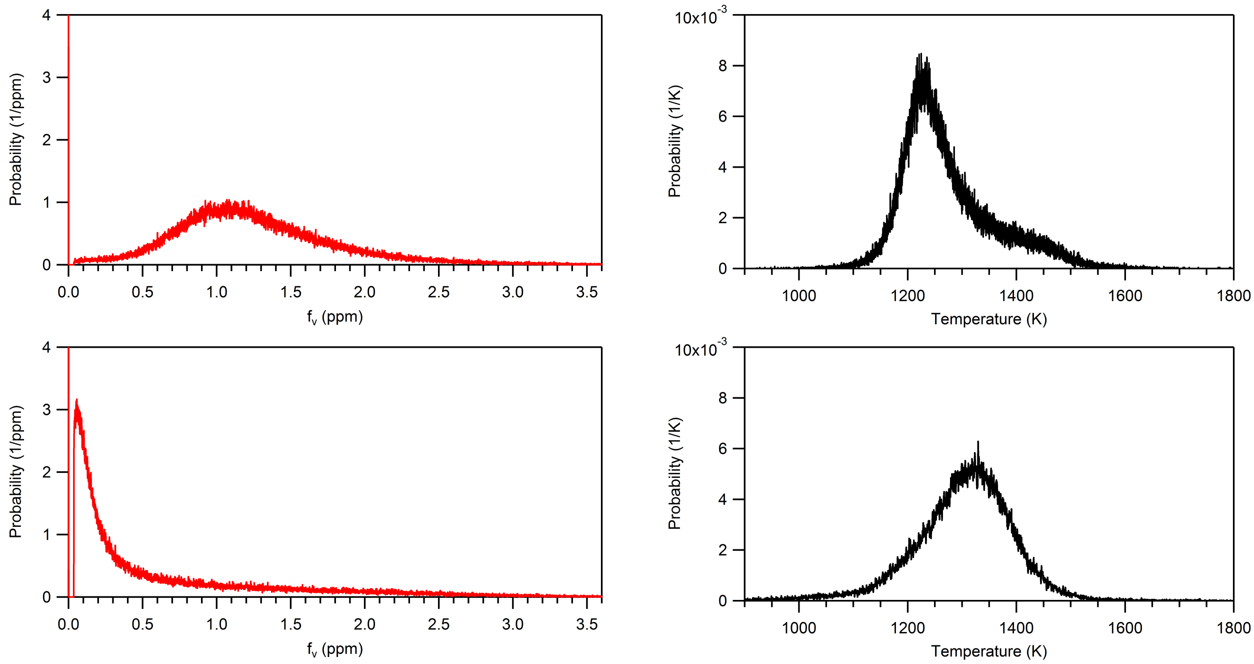

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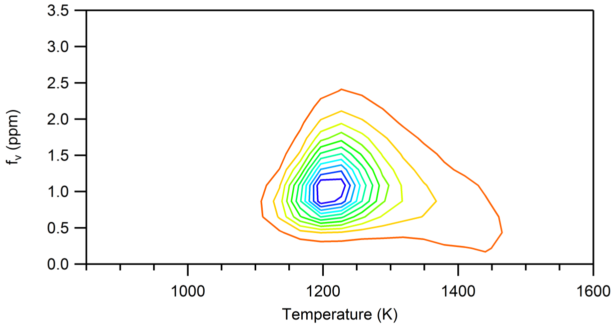

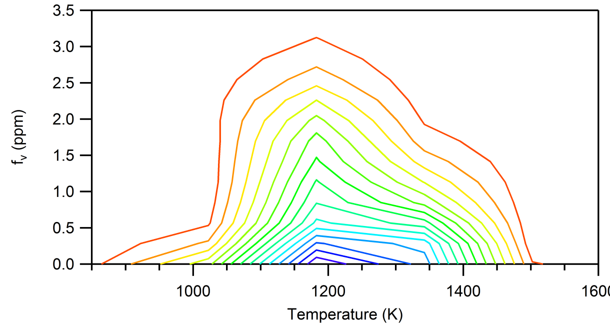

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