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REAL-TIME QUANTITATIVE 2-D IMAGING OF WATER VAPOR IN DIFFUSION FLAMES

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ABSTRACT

An *imaging* Wavelength Modulation Spectroscopy (WMS) system has been developed for measuring *combustion species concentrations* in two-dimensional or axisymmetric flames. This system uses a rastered near-infrared diode laser that provides a two-dimensional absorption image. This technique has the advantage over other laser-based methods as being simple and inexpensive to implement, provides signals which are directly linear in concentration, and is easily calibrated to provide accurate quantitative results. This technique can generate absorption (or concentration) "movies" at real time rates, showing steady and transient behavior of species within the flame. Qualitative absorption data can be converted into quantitative concentrations using a numerical absorption model that utilizes the HITRAN database. Currently, this system is being used to measure water vapor absorbances in steady and transient methane/air flames from a Wolfhard-Parker slot burner.

INTRODUCTION

To bridge the gap between chemistry and fluid mechanics in combustion, especially in microgravity combustion measurements, species concentrations and temperature profiles are needed throughout the flame. However, many techniques, invasive and non-invasive, are limited to point or line-of-sight measurements that cannot provide quantitative data over a larger physical domain. Other systems are not compatible with experiment environments that limit the size, weight, and/or power requirements of the diagnostic, which are typical of NASA's reduced-gravity facilities. These considerations, have generally limited microgravity combustion studies to the capture of flame emissions on film or video,[1-3] laser Schlieren imaging,[4] and (intrusive) temperature measurements using thermocouples. Given the development of detailed theoretical models, more sophisticated studies are needed to provide the kind of quantitative data necessary to characterize the properties of microgravity combustion processes as well as provide accurate feedback to improve the predictive capabilities of the computational models.

This paper reports on an innovative *imaging* high-frequency Wavelength Modulation Spectroscopy (WMS) system developed by Southwest Sciences. Over the past ten years, Southwest Sciences has focused its research on the high sensitivity, quantitative detection of gas phase species using diode lasers. FM spectroscopy or high frequency wavelength modulation spectroscopy has been applied to sensitive absorption measurements using visible or near-infrared GaAlAs or InGaAsP diode lasers,[5] as well as lead-salt lasers in the mid-infrared spectral region.[6] Because these lasers exhibit essentially no source noise at the high detection frequencies employed with this technique, the achievement of sensitivity approaching the detector shot noise limit is possible. Such high sensitivity permits the *in situ* detection of chemical species of interest such as H_2O, CH_4, O_2, CO, CO_2, OH, *etc.* at bandwidths approaching MHz ranges. The technique described in this paper has the advantage over other laser-based methods as simple and inexpensive to implement, provides signals which are directly linear in concentration, and is easily calibrated to provide accurate quantitative results. In addition, this system is capable of taking seconds of video-rate images (i.e., "movies") of strong absorbers in flames under 1-g and microgravity environments.

Initial experiments with this imaging system include obtaining time-dependent water vapor absorbance images of a two-dimensional diffusion flame in normal-gravity using WMS and a near-infrared diode laser. The strong absorption line strength of water make detection by optical means attractive and allows 2-D absorption images to be obtained in real time.

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WAVELENGTH MODULATION SPECTROSCOPY

WMS is a technique used to measure weak absorption signals slowly or, alternatively, strong absorption signals at a high bandwidth. Unlike direct absorption, the detection sensitivity is limited by detector quantum noise and not by laser $1/f$ noise. This can improve the detection sensitivity by 3-4 orders of magnitude. This technique has been described in considerable detail in two recent publications, including comparisons with other high frequency diode laser detection methods (e.g., one- and two-tone frequency modulation spectroscopy).[6] In addition, these methods were previously applied to the measurement of water vapor in microgravity diffusion jet flames.[7]

Briefly, this method, which is an extension of diode laser "derivative spectroscopy" techniques widely used at kHz frequencies, involves a superposition of a small sinusoidal modulation at frequency f on the diode laser injection current. In the small modulation limit, the WMS lineshape is the n^{th} derivative of the original molecular absorption lineshape. In practice, the modulation depth is set at a value to maximize the signal level and, in this regime, lineshapes only approximate derivatives, but can be readily calculated.

Detection bandwidths of ~ 100-200 kHz are required to obtain images in real time. To support this bandwidth, frequency modulations of 5 MHz and 364 kHz are superimposed on the diode laser to allow the detection band to be moved down to frequencies compatible with digitizing electronics. The signal is demodulated at 10 MHz before digitization. A second, digital demodulation at 364 kHz extracts the absorption signal. This lower frequency modulation allows multiple sampling of the peak-to-trough amplitude of the high frequency $2f$ signal, nulling baseline effects.[8]

EXPERIMENTAL HARDWARE

The optical layout is fairly simple, as shown in Fig. 1. The laser beam is collimated by an anti-reflection coated aspheric lens to a diameter of ~1 mm and is pointed onto an X-Y optical scanner placed at the focus of an off-axis paraboloid. This scanner rasters the laser beam across the flame. A second off-axis paraboloid focuses the beam onto a single detector. This device has an image rate of approximately 238,000 pixels per second allowing a 100×100 array to be obtained at a rate of 23.8 Hz (42 ms per frame). This high data rate is attainable because of the large signal-to-noise obtained when using WMS. Raster scanning also allows the amount and position of the scan to be controlled so that different parts of the flame may be analyzed at varying temporal and spatial resolutions.

The system uses a near-infrared 1.4 μm laser diode tuned to a water vapor absorption line whose line strength is optimal at 1800 K. Initial tests indicate a signal-to-noise of 60 with a bandwidth of 182 kHz for absorbances of ~2-3% due to this(7,6,2)←(7,6,1) transition at 7179.75 cm^{-1} of the $\nu_1+\nu_3$ combination band.

Experiments are performed using a two-dimensional methane/air diffusion flame produced with a Wolfhard-Parker slot burner shown in Fig. 2. Flow rates of 1.6 and 12.6 liters per minute for fuel and air respectively are based on flow velocities used by Smyth, et al.[9] for a similar burner. The central fuel slot is 0.8 cm wide and 3.8 cm in length; the two outer (air) co-flow slots are each 1.6 cm wide and 3.8 cm in length. The laser raster scan configuration used for these experiments provides a 2.5 cm x 2.5 cm scan area nearly centered on the fuel slot as

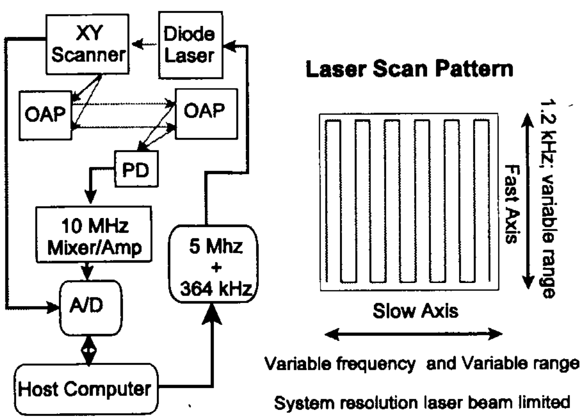

Figure 1 - Schematic diagrams of the imaging WMS system and the laser scan pattern. A wavelength modulated diode laser is raster scanned across a flame using an XY scanner and an off-axis paraboloid (OAP) mirror. Another OAP focuses the scanning diode laser onto a photodiode detector (PD). The data is read via a fast A/D and recorded on the host computer. (The flame is located between the two mirrors.)

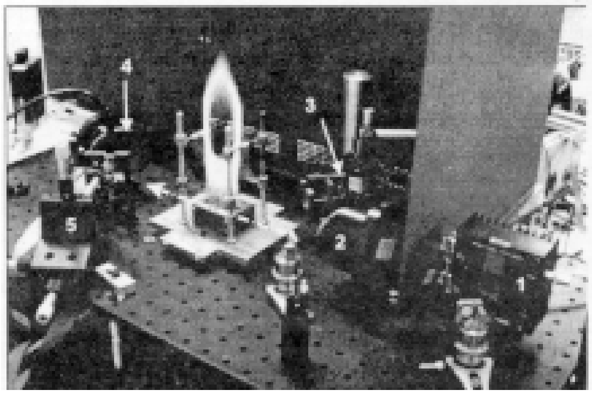

Figure 2 - Two-dimensional imaging system. The dotted arrow indicated the direction on the beam. Numbered components in the figure are: 1. diode-laser; 2. OAP; 3. X-Y scanner; 4. OAP; and 5. detector assembly.

indicated in Fig. 3. The base of the scan is positioned just above the surface of the burner. Two stabilization screens, shown in Figs. 2 and 3 are used to reduce flame flicker. All experiments were conducted in ambient air, with a nominal ambient pressure of 0.79 Atm; Southwest Sciences is located in Santa Fe, NM which has a nominal elevation of 7000 ft.

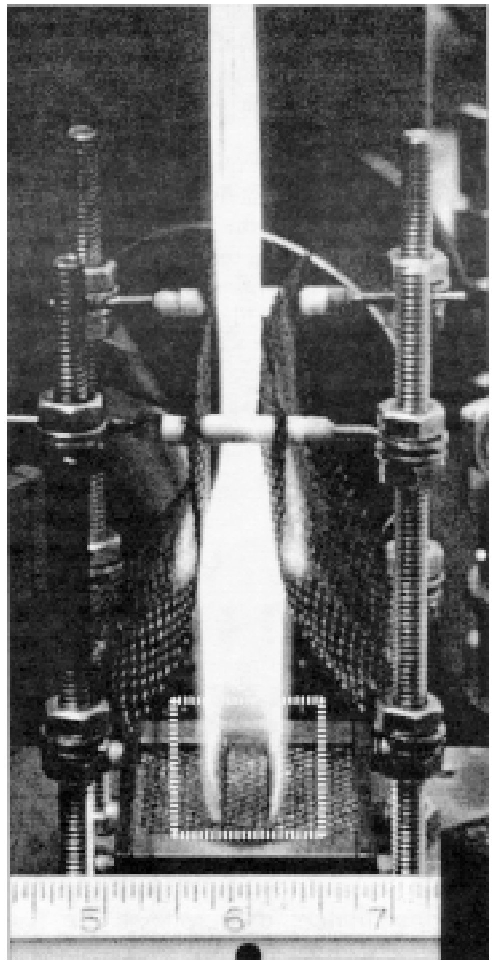

Figure 3 - Two-dimensional diffusion flame produced using a Wolfhard-Parker slot burner. The laser beam path is orthogonal to the ruler in the image. (Scale in inches.) The scan region (2.5 cm x 2.5 cm) is indicated by the dotted outline near the burner surface.

EXPERIMENTAL RESULTS

This experiment generates four channels of data. The first two channels are from the detector: a time varying component (AC) and a slower, constant value (DC). The remaining two channels are the X and Y positions of the laser beam as it is rastered through the test region. All four channels are acquired by a PC-based data acquisition system at a rate of 2.1 MHz per channel.

Since the laser beam is focused onto a single location on the detector, the absorbance data must be mapped to its location within the scan area using the X-Y position data provided by the scanners. In addition, the scanners output a series of bit markers that are used to determine the start of a scan sweep and the start of an image frame. Once re-mapped, the absorbance data and the XY position data can be used to create images of the water vapor absorbance within the flame (Figs. 4, 6, and 8). The normalized absorbance images in Figs. 4 and 6 are of steady flames. The X and Y scales are also normalized such that the scan region is from -1 to +1. High absorbance regions are bright (white), while low absorbance regions within the flame are dark. Fuel and air flow upwards in the images, with the fuel entering from the bottom center ($X \sim 0$); the air flows are on either side of the fuel flow($X \sim \pm 0.4$).

The dark triangle at the bottom of the image in Fig.4 indicates little to no hot water vapor, at the location at which the methane enters the combustion region. The bright, inverted "V" shaped area in the central region of the scan indicates the presence of a much larger amount of hot water vapor, which is being produced within the flame. The two vertical dark regions on either side of the inverted "V" high absorbance water vapor region are the air co-flow jets that have a low water vapor concentration. Absorption profiles for two different elevations for this image in are shown in Fig. 5. Note that the relatively low absorbance of the fuel jet and the air co-flows are distinct features in the profiles, as are the high water absorbance regions.

The absorption image in Fig. 6 is of a flame with a low methane flow rate; approximately 5% of the rate used to obtain the image in Fig 4. In this case, the region of high water vapor absorption is near the burner surface and the image centerline (X~0). This is shown clearly in the absorption profiles shown in Fig. 7.

The absorbance images in Fig. 8 show a perturbed flame; a forced flow of air from left to right interacts with the steady flame shown in Fig. 4. The individual frames are 42 milliseconds apart. As with the previous images, high absorbance regions are bright (white), while low absorbance regions within the flame are dark.

CONCLUSIONS

An imaging Wavelength Modulation Spectroscopy system has been developed and applied to measuring water vapor absorbances in a two-dimensional diffusion

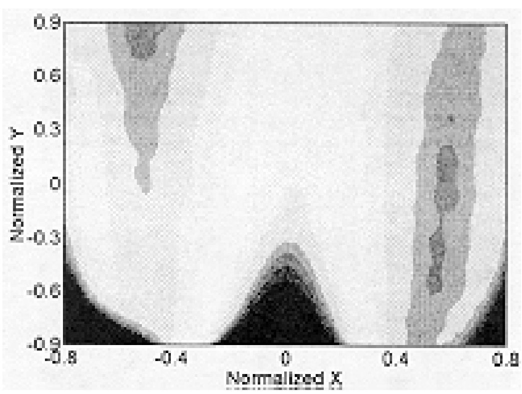

Figure 4 - Normalized water vapor absorbance image from a methane/air flame in a Wolfhard-Parker slot burner. White regions contain the highest absorbance, dark regions the lowest. (Methane and air flow velocities are in stoichiometric proportion, yielding volumetric flow rates of 1.6 and 12.6 standard liters per minute respectively.)

Figure 6 - Normalized water vapor absorbance image from a methane/air flame in a Wolfhard-Parker slot burner. White regions contain the highest absorbance, dark regions the lowest. (Methane volumetric flow rate is 5% of the rate used in Fig. 4)

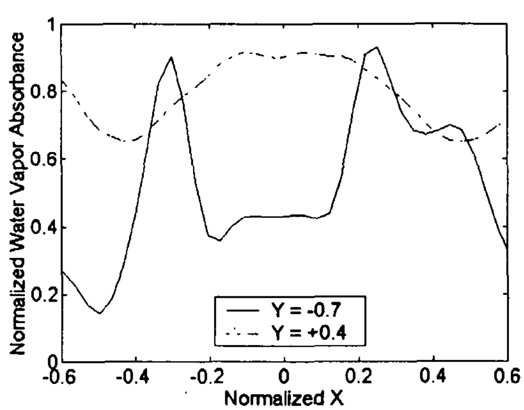

Figure 5 - Normalized water vapor absorbance profiles for the methane/air flame absorbance image in Figure 4.

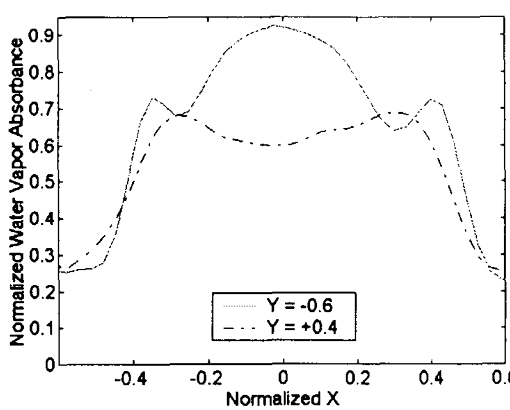

Figure 7 - Normalized water vapor absorbance profiles for the methane/air flame absorbance image in Figure 6.

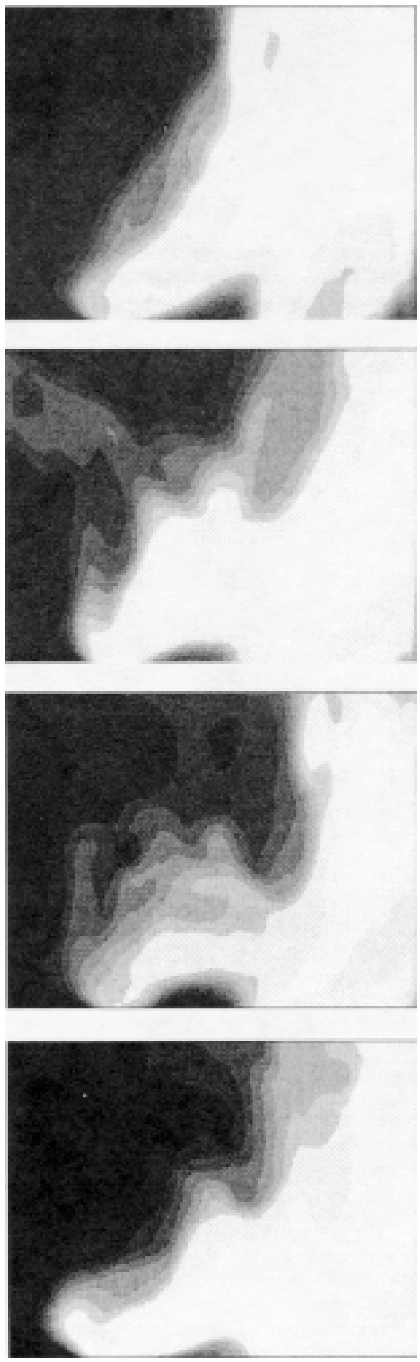

Figure 8 - Normalized water vapor absorbance images from a methane/air flame with a forced flow of air from left to right. White regions contain the highest absorbance, dark regions the lowest. Images are 42 milliseconds apart.

flame. The images presented show that this technique can resolve both small spatial and temporal changes within a flame, as shown by the image sequence in Fig. 8. This system captures images at a rate of 23.8 Hz (42 ms per frame), which can be played back as a "movie". In addition, the data exhibits an excellent signal-to-noise ratio.

Future plans for this system include obtaining quantitative concentrations and temperatures from the absorbance data. This will require a parametric study to examine the effects of temperature and number density on water vapor absorption behavior. An expected result of this study is the creation of a three-dimensional absorption surface that is a function of both temperature and number density. In addition, future experiments will include comparisons of water vapor and methane concentrations in both normal-gravity and reduced-gravity diffusion flames using either a Wolfhard-Parker slot burner, or a porous cylinder.

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