N96-15595

# QUANTITATIVE MEASUREMENT OF OXYGEN IN MICROGRAVITY COMBUSTION

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## Introduction

A low-gravity environment, in space or in ground-based facilities such as drop towers, provides a unique setting for studying combustion mechanisms. Understanding the physical phenomena controlling the ignition and spread of flames in microgravity has importance for space safety as well as for better characterization of dynamical and chemical combustion processes which are normally masked by buoyancy and other gravity-related effects. Due to restrictions associated with performing measurements in reduced gravity, diagnostic methods which have been applied to microgravity combustion studies have generally been limited to capture of flame emissions on film or video, laser Schlieren imaging and (intrusive) temperature measurements using thermocouples. Given the development of detailed theoretical models, more sophisticated diagnostic methods 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 models. When the demands of space flight are considered, the need for improved diagnostic systems which are rugged, compact, reliable, and operate at low power becomes apparent.

This research builds on our earlier work[1] and combines two innovations in an experimental system which should result in a new capability for quantitative, nonintrusive measurement of major combustion species. Using a newly available vertical cavity surface-emitting diode laser (VCSEL) and an improved spatial scanning method, we plan to measure the temporal and spatial profiles of the concentrations and temperatures of molecular oxygen in a candle flame and in a solid fuel (cellulose sheet) system. The required sensitivity for detecting oxygen is achieved by the use of high frequency wavelength modulation spectroscopy (WMS).[2-3] Measurements will be performed in the NASA Lewis 2.2-second Drop Tower Facility.

The objective of this research is twofold. First, we want to develop a better understanding of the relative roles of diffusion and reaction of oxygen in microgravity combustion. As the primary oxidizer species, oxygen plays a major role in controlling the observed properties of flames,

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Program Starting Date: 28 June 1994.

including flame front speed (in solid or liquid flames), extinguishment characteristics, flame size and flame temperature. The second objective is to develop better diagnostics based on diode laser absorption which can be of real value in microgravity combustion research. We will also demonstrate diode lasers' potential usefulness for compact, intrinsically-safe monitoring sensors aboard spacecraft. Such sensors could be used to monitor any of the major cabin gases as well as important pollutants.

## Experimental Approach

A schematic of the experimental setup is shown in Fig. 1. The output of the diode laser is focussed onto an optical scanning mirror positioned at the focus of an off-axis paraboloidal (OAP) reflector. Since all light rays emanating from this point are reflected along parallel paths by the OAP, this results in a collimated laser beam (~1 mm dia.) which linearly traverses the flame region as the mirror is scanned. A second OAP refocuses the beam onto a single detector. The mirror pair is configured so that the total optical path at any transverse position is nearly constant.

This arrangement permits a temporal map of concentration and temperature of $O_2$ to be obtained during the microgravity experiment. In a typical run, the mirror is dithered back and forth at a rate of 20 Hz, so that the laser samples a 4 cm wide region encompassing the flame. As the mirror is moved, an absorption spectrum is recorded at 1 mm spatial resolution. The laser wavelength sweeps across two adjacent absorption lines. From these data, the temperature and concentration of $O_2$ can be recovered for each spatial element as a function of drop time. For the candle flame experiments, where the profiles of interest are radially distributed from the flame center, Abel inversion techniques are used to convert the measured projection spectra to radial profiles for selected heights in the flame.[1,4]

In our prior work,[1] an eight line-of-sight fiber optic system measured water vapor mole fractions in the NASA Lewis 2.2-sec Drop Tower. The electronic modulation and detection circuitry developed in that program will be used here. The spatial scanning mechanism now used has the advantage that much higher spatial resolution is achieved with a concurrent simplification in complexity and size of the detection electronics. A single detection channel sequentially records all spatial information, which avoids problems associated with multiple detection channels (relative calibrations, drift, cost, etc.) A commercial state-of-the-art digital signal processing (DSP) data acquisition board is used to generate both the mirror dithering and laser ramp waveforms, as well as acquire, pre-process, and store all the data. This board will be controlled by a stand-alone 486 computer board. All of the electronics (including the computer) will be housed in a small enclosure which will be mounted on the drop rig.

This program utilizes a new type of diode laser. Vertical cavity surface-emitting lasers, which are now available at selected wavelengths below 1 $\mu$m, are true single-mode devices. Unlike the Fabry-Perot GaAlAs lasers typically used in this spectral region, VCSEL lasers can be scanned without mode-hopping over a relatively large wavelength range (3 nm). We have obtained custom VCSEL lasers at 760.3 nm, chosen to access a pair of $O_2$ rotational lines in the $b^1\Sigma$-$X^3\Sigma$ electronic transition.

Wavelength Modulation Spectroscopy

In traditional absorption measurements, the spectral lineshape is obtained by subtracting the signal transmitted through the absorbing medium from a reference (no absorber) spectrum. The factor limiting detection sensitivity is source noise, and limits of $10^{-3}$ fractional absorption are common. High frequency wavelength modulation absorption spectroscopy allows the measurement of much weaker optical absorbances by shifting the detection band to high frequencies where excess laser source noise becomes unimportant. For WMS, a small sinusoidal modulation is superimposed on the diode laser injection current. This current modulation produces a modulation of the laser wavelength. Typically, the amplitude of the current modulation is chosen so that the induced wavelength modulation is comparable to the width of the spectral feature under study. Phase-sensitive electronics are then used to detect the signal at the second harmonic of this frequency.

Diode laser intensity noise power per unit frequency has been found to decrease rapidly at higher frequencies. Therefore, improved sensitivity is attained by modulating the laser wavelength at megahertz frequencies. In this way we have achieved fractional absorption sensitivities at the near shot-noise limit ($\sim 10^{-7}$) for both near- and mid-IR diode lasers.[3] For the greatest sensitivity, WMS (or lower frequency harmonic detection) has usually been implemented using a "sweep and fit" approach. The laser is modulated and scanned in wavelength across the absorption feature; the entire $2f$ WMS spectrum is recorded. By numerical fitting techniques (multilinear regression, matched filtering, etc.) the measured $2f$ lineshape is compared to a calibrated value so as to determine the absolute sample concentration.

Given the flexibility of the data acquisition system, both in-phase and quadrature components of the phase-sensitive detector output will be recorded. Thus the detection phase does not have to be preset and can be optimized during data analysis. Also, the dc photocurrent will be acquired as well. This signal is proportional to the laser intensity ($I_0$) and is used to account for all variations in alignment, beam attenuation, etc.

Measurement of Oxygen Mole Fraction and Temperature

The absolute absorber concentration N is related to the WMS signal by

$$Signal = C \cdot \alpha \cdot f_{WMS}, \quad \text{where} \quad \alpha = \sigma N l, \tag{1}$$

and C is a system electronic calibration constant, $f_{WMS}$ is a factor relating the WMS signal to the direct absorption peak value (approximately 0.6), $\alpha$ is the absorbance, $\sigma$ the absorption cross section and $l$ is the absorption path length. Given the system temperature and pressure, the absolute concentration is linearly proportional to the measured signal and is readily obtained.

The optimum spectral lines for use in simultaneously measuring temperature and concentration (or mole fraction) of $O_2$ have been determined. Our goal is to use two closely spaced, but not overlapping, lines where the composite numerical factor which is used to convert signal to mole fraction should be very sensitive to temperature for one of the lines, and insensitive for the other, over the flame temperature range of interest. In this manner we can use a single line to get mole fraction without accurately knowing the temperature profile, or we can use the signal peak ratios to obtain temperature.[5] We have identified four pairs of lines which exhibit these characteristics. These pairs lie in the 759 to 761 nm wavelength range. The best pair shows a temperature sensitivity of 47% ratio change per 100 K in the range 1300-1800 K. The best temperature independent line in this region has a constant conversion factor (±5%) between 1000 and 1650 K. Since we should be able to measure signal height ratios to better than 5%, the expected temperature accuracy (assuming we have an accurate knowledge of all spectral parameters) is ±25 K.

## Results

At this point in the program, we have tested a benchtop layout of the optics. It appears that the dither scanner can readily move a collimated beam of diameter ~1 mm back and forth across the required 40 mm range at 20 Hz. The laser power on the detector was flat to better than 2% during these scans (although any variations will be accounted by measurement of $I_0$). The DSP board has been programmed to generate both laser and scanning waveforms and can acquire the $2f$ spectra. We have received and are now characterizing the VCSEL lasers. We plan to begin preliminary benchtop candle flame measurement shortly.

## References


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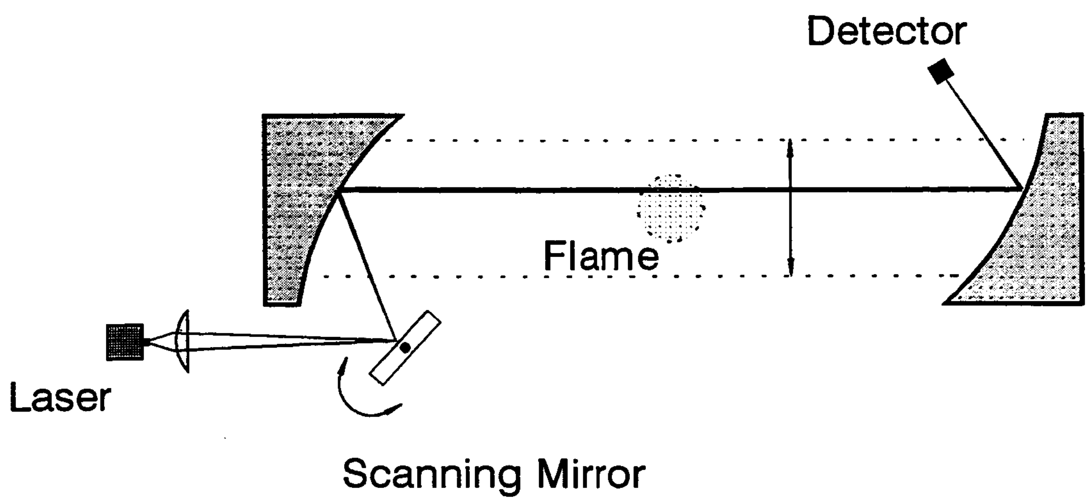


Figure 1 - Schematic of Optical Setup.