

# Preliminary study of Temperature and Water Vapor Concentration in a Scramjet Combustor Using a Software for Spectra Simulation

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## Abstract

The aim of this work is to verify the possibility of applying diode laser spectroscopy to obtain water vapor temperature and concentration in a scramjet combustor that will be constructed in the lab of IEAv. Employing a homemade software to simulate water vapor spectra in the 1391 nm and 1343 nm diode lasers regions, it was found that there are four good lines for the measurement..

## Introduction

A **scramjet** (supersonic combustion **ramjet**) is a variation of a **ramjet**. Within the engine, fuel is injected into a supersonic airflow. The design of the combustion chamber may incorporate features such as cavities in the sidewalls, to induce recirculation zones and act as flame holders. The flow out the rear of the engine is expanded through a diverging nozzle. Design of a combustor requires detailed knowledge of the fuel - air mixing mechanism and the combustion mechanism.

Two-line, time-multiplexed diode laser absorption spectroscopy will be applied to a scramjet combustor to measure water vapor temperature and concentration. The measurement will be made in a Hypersonic Shock Tunnel located in the Laboratory of Aerothermodynamics and Hypersonics, IEAv-CTA. This Hypersonic Shock Tunnel can be used to produce high, medium and low enthalpy hypersonic flow conditions. The viability of the method was demonstrated by Griffiths and Houwing [1]. Figure 1 shows the experimental apparatus layout and Figure 2, the test zone photo and a scramjet scheme. Gases exist at the test plane for approximately 500  $\mu$ s following each detonation. High temperature H<sub>2</sub>O typically remains at the test plane for a much longer time (>100 ms) due to combustion occurring in the blowdown following each detonation.

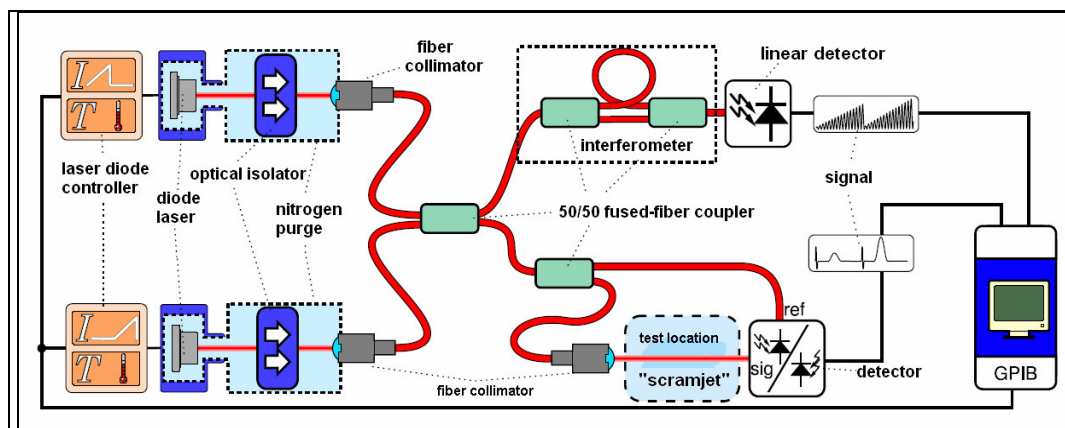
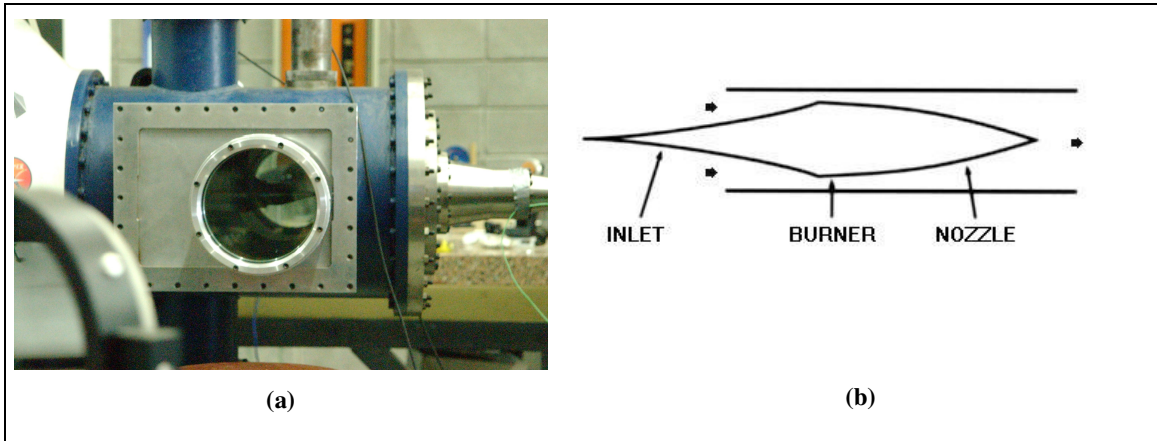


Figure 1: Experimental layout [1].



**Figura 2.** (a) Photo of the test zone (IEAv), (b) Scramjet scheme.

The application of absorption spectroscopy, using diode lasers, for thermometry and species measurement has been well established previously [2]. The theory that underpins the technique is also well established so only a brief outline of the theory is presented. As a monochromatic beam from a diode laser passes through an absorbing medium, the transmitted intensity of the beam,  $I$ , is related to the initial intensity,  $I_0$ , by the Beer–Lambert relation:

$$I = I_0 \exp(-k_\nu l) \quad (1)$$

where  $k_\nu$  is the frequency-dependant absorption coefficient and  $l$  is the path length. If an absorption line, of species  $i$  in some gas mixture, is sufficiently isolated from other spectral features then  $k_\nu$  is a function of the strength,  $S(T)$ , and shape,  $g(\nu)$  where  $\int g(\nu) d\nu = 1$ , of the absorption line and the number density,  $N_i$ , of the molecular species. This relation is given by:

$$k_\nu = S(T)g(\nu)N_i \quad (2)$$

so that  $k_\nu$ , as well as depending on frequency, depends on the temperature,  $T$ . For the case of multiple overlapping spectral lines,  $k_\nu$  is treated as a sum over the individual spectral lines.

If  $S(T)$  is known, then equation (2) can be used to find  $N_i$  by integrating absorbance over frequency. This requires knowledge of the temperature, which can be found by probing a second absorption line.

Thermometry relies on the dependence of line strength on temperature [8]:

$$S(T) = S(T_0) \frac{Q(T_0) \exp(-c_2 E''/T)}{Q(T) \exp(-c_2 E''/T_0)} \cdot \frac{[1 - \exp(c_2 \nu_0/T)]}{[1 - \exp(c_2 \nu_0/T_0)]} \quad (3)$$

where the line strength measured at a reference temperature,  $S(T_0)$  is scaled to an arbitrary temperature  $T$ . This scaling function depends on the lower-state energy of the transition,  $E''$ , the frequency of the transition,  $\nu_0$ , and the total internal partition sum of the molecule,  $Q$ , which can be computed using the method of Fischer *et al.* [3]. Also appearing in the expression is the second radiation constant,  $c_2 = hc/k$  where  $h$  is Planck's constant,  $c$  is the speed of light and  $k$  is Boltzmann's constant.

From equation (3) we see that if we choose two spectral lines of different  $E''$  and similar  $\nu_0$  then the ratio:

$$R(T) = \frac{S_1(T)}{S_2(T)} = \frac{S_1(T_0)}{S_2(T_0)} \exp \left[ -c_2 (E_1'' - E_2'') \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \quad (4)$$

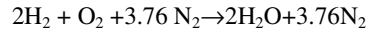
is a function only of  $T$ . Therefore, if an experimental system is arranged in such a way so as to measure the integrated spectral absorption of two spectral lines with different lower-state energies then both temperature and species concentration can be deduced. Furthermore, the sensitivity of the thermometry can be tuned to a particular temperature range by choosing spectral lines with appropriate  $E''$ .

## Spectra simulation

The free software ReadHi has been written in the C++ Builder Language for Windows [4]. The spectral constants necessary for this simulation (such as line positions, integrated intensities at 296 K, air-broadened and self-broadened halfwidths) can be found in HITRAN and HITEMP database [5,6]. The spectra are simulated considering a Voigt line shape, resulting from the convolution of the Lorentz profile (collision broadening due to pressure effects) with the Gaussian function (Doppler line shape due to temperature effects). The software allows the simulation of the spectra with various experimental conditions and it is possible to vary the total and partial pressures of the molecules, the path length and the temperature. The simulated spectrum is shown on the screen

and it is possible to store the data (wave number versus the absorbance) in ASCII. The software supplies the position and the intensity of the resultant peaks in the spectrum. It is useful to obtain the data of intensity ratio between absorption peaks in function of the temperature, important in flame temperatures determination using diode laser spectroscopy.

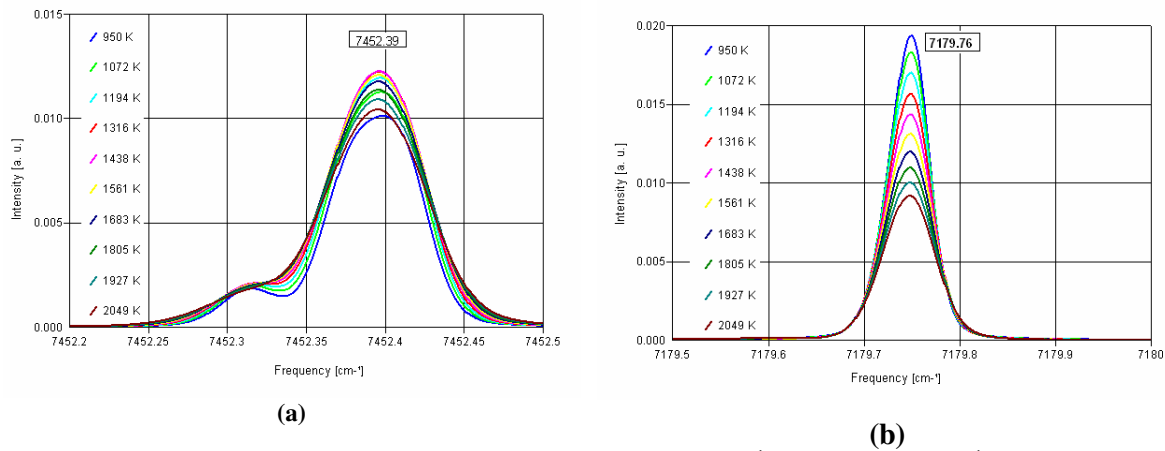
The conditions for spectra simulation (pressure and water vapor molar fraction  $-x_w$ ) were calculated considering the following reaction (molar fraction of water vapor for a complete and stoichiometric reaction =0.35):



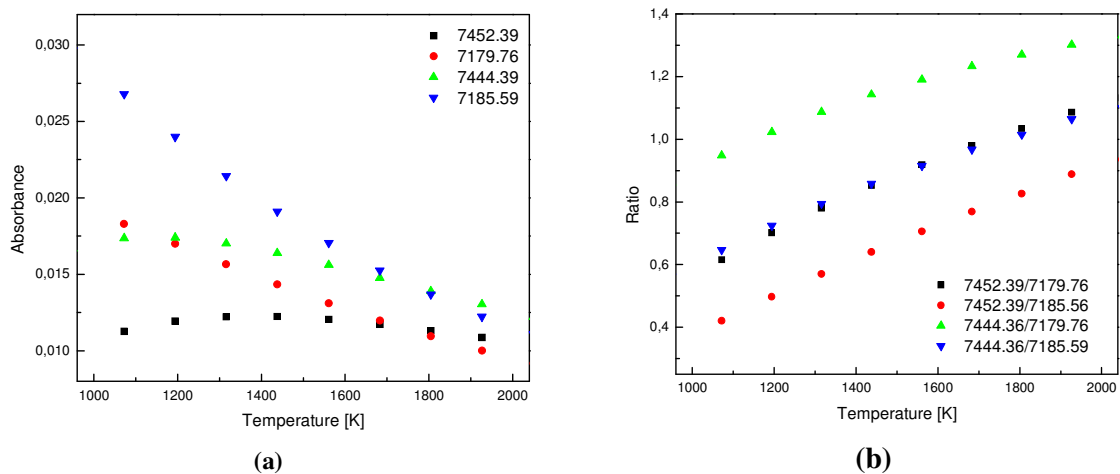
The tunnel was configured to produce a pressure of about 70 mbar in the test zone. The spectra were simulated between 1000 K and 2000 K in the emission region of the lasers DFB 1391 ( $7190 \text{ cm}^{-1}$ ) and DFB 1343 ( $7446 \text{ cm}^{-1}$ ).

## Results and Discussions

Some of the water-simulated spectra are shown in Figure 3. Figure 4 shows the best lines for the experimental measurements in the analyzed lasers regions.



**Figure 3:** Simulated spectra by the ReadHi software (a) line  $7452.39 \text{ cm}^{-1}$  (b) line  $7179.76 \text{ cm}^{-1}$ .



**Figure 4:** (a) Intensities and (b) intensities ratio for the best lines of the lasers analyzed (1 cm of path length).

The four vapor water absorption lines ( $7179.76 \text{ cm}^{-1}$ ,  $7185.59 \text{ cm}^{-1}$ ,  $7444.39 \text{ cm}^{-1}$ ,  $7452.4 \text{ cm}^{-1}$ ) present equivalent intensities and can be used for thermometry in the experiment.

## Conclusions

The preliminary study has shown that the diode laser spectroscopy is adequate for scramjet combustor characterization. The method will be employed to obtain quantitative, *in situ* measurements of gas temperature and H<sub>2</sub>O concentration.

## References

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