

# **Radiative Properties of Water Vapor by Optical Study of Hydrogen–air Combustion**

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## **1. INTRODUCTION**

There are ever more stringent restrictions on the emission and monitoring of harmful pollutants from combustion processes. To contribute to the development of more competitive combustors (internal combustion engine, gas turbine, ramjet) by the command of heat exchanges, the determination of temperature  $T$  and concentration distributions of combustion products is required. Under severe conditions ( $T > 2000$  K and elevated pressure), we can't set up or calibrate the conventional intrusive sensing techniques (thermocouple, suction probe). Therefore, an optical study based on emission spectroscopy of gas species has been developed [1], [2]. This method consists in measuring the emitted radiation of the gas in a precise spectral region. Because emission spectra are directly influenced by gas species, composition and concentrations, a theoretical and experimental analysis of typical combustion samples has to be investigated for precise modeling.

Spectroscopic parameters (spectral line frequency indicating the line position, absorption intensity, transition moments and broadening coefficients) were first compiled in the high-resolution transmission molecular absorption database (known under the acronym HITRAN) at the atmospheric conditions of temperature and pressure [3]. Moreover new transitions and bands which are significant at higher temperatures have been included in the line-by-line compilation named HITEMP. However these parameters from which a wide variety of computation simulation codes are able to calculate and predict the transmission and emission of radiation in combustion processes are not validated at pressures higher than one atmosphere [4]. Accurate experimental results not only on line frequency and intensity but also on half-widths are crucial to retrieve temperature and concentration from the measured spectra at high pressure.

In our laboratory we have designed an experimental set up to analyze line broadening of high pressure combustion products in a transient phenomenon. In this paper we present initial spectroscopic measurements. We have specifically studied the high temperature and pressure properties of water vapor, produced as a burnt gas from a confined combustion of a reactive hydrogen-air mixture for different initial conditions.

## **2. EXPERIMENTAL FACILITY**

So far temperature distributions of combustion gases were retrieved from a quadratic criteria minimization of  $\text{CO}_2$  infrared emission spectrum in the band head region ( $\nu_3$  : 2380 - 2400  $\text{cm}^{-1}$ ) [1] thanks to a line by line modeling of the spectrum of this molecule [5], [6]. Some measurements carried out on industrial test beds were in good agreement with the results of intrusive techniques but they showed that the retrieval method can be applied only for

pressures lower than 4 bar. For the higher pressures, the line broadening is too wide to analyze the measurements.

Hence, to extend the optical method to severe conditions, water vapor has been selected.  $H_2O$  plays a predominant role among the main combustion products : it is a major contributor to radiative heat exchanges and its spectrum involves a great number of lines. We have designed and implemented a combustion chamber for dynamic emission measurements of  $H_2O$  up to 200 bar. Static test beds can not actually produce static flames over 20 bar (technological problems of flame stability and tightness).

## 2.1. Explosion vessel

The confined combustion of a stoichiometric hydrogen-air mixture produces  $H_2O$  molecules for different temperature and pressure conditions. The high pressure cell for these measurements is shown in Fig. 1. The vessel consists of a stainless steel, cylindrical tube of 600 mm length, 150 mm inner diameter and 25 mm thickness closed by two 25 mm thickness stainless steel flanges. Once primary vacuum has been stabilized in the chamber, the fuel and oxidizer are controlled by two mass flow controllers and mixed in the pipes which carry the mixture inside the combustion chamber.

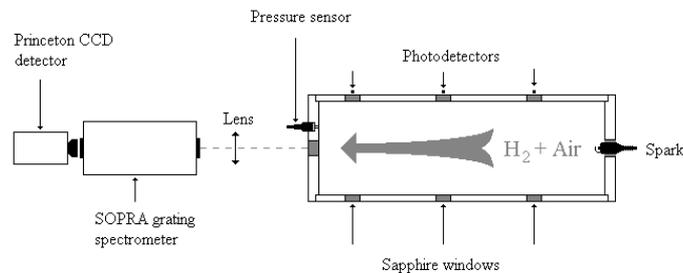


Figure 1 : Schematic of the high pressure cell.

A static pressure transmitter (type CERALINE) checks the initial pressure in the enclosure and a spark is used for producing an electrical discharge to light up the gaseous mixture. Moreover a piezoelectric sensor in the 0-250 bar range (Kistler model 6061B) measures the evolution of dynamic pressure during the combustion.

## 2.2. Optical apparatus

The enclosure is equipped by different sapphire windows (20 mm diameter and 5 mm thick) which can withstand pressures up to 200 bar. One of these is mounted in the middle axis of the end flange and provides an optical access for the water emission measurements. A collecting lens ( $f = 100$  mm) is used to focus the emitted radiation on the entrance curved slit of the high resolution grating spectrometer SOPRA model UHRS F1150 (Fig. 1). This 1150 mm focal length spectrometer with a 600 g/mm grating blazed at  $1.6 \mu m$  achieves a linear dispersion of 0.633 nm/mm at 800 nm. To capture the signal beam, a Princeton Instruments camera Spec-10:400B is coupled to the spectrometer's exit focal plane. The fast spectral acquisition (400 spectra/sec) of this digital camera system with full-vertical binning was used to record multiple water emission spectra during the explosion.

Optoschmitt IC photodetectors were also mounted on the three side windows (Fig. 1) to have information of the flame velocity. Because the purpose of this study is to analyze the pressure effects on line broadening, velocity measurements will be extremely helpful to correlate pressure measurements to the thermodynamic conditions of the water emission spectra.

### 3. EXPERIMENTAL RESULTS AND DISCUSSION

#### 3.1. High pressure and velocity measurements

All the tests concern the study of water vapor produced from combustion of a stoichiometric hydrogen-air mixture. Because we were doing spectra at elevated pressures, our primary interest was to validate the experimental set up and the evolution of the dynamic pressure during combustion. According to the pressure results, we note that the test bed is efficient and pressures from 10 to 80 bar were measured at the end of combustion with a 2 % relative precision [7]. According to the Fig. 2 which results from series of tests, pressure at the end of explosion roughly varies as the initial pressure  $P_i$ .

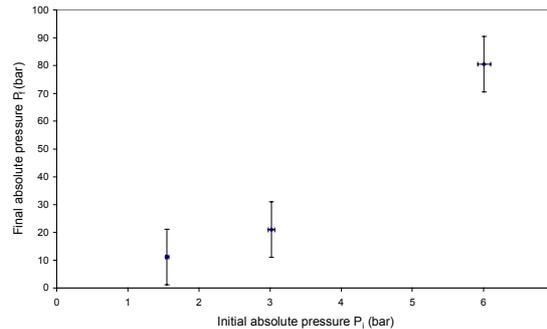


Figure 2 : Maximal pressure versus initial pressure.

Primary results of flame velocity measured for the same initial conditions gave an average value of 13.65 m/s for combustion of a stoichiometric  $H_2$ -air mixture at 9.8 bar final absolute pressure.

#### 3.2. Spectroscopic measurements

In the broad spectrum of water, we selected few isolated lines in the 0.8  $\mu m$  band in order to limit the effects of the nearest lines. We performed emission measurements in the 815-820 nm region with the fast spectral acquisition of 400 spectra/sec. In Fig. 3 spectra intensities are plotted at three different times. Here at the end of combustion the maximal pressure was 17.9 bar. Despite an intense continuous background, these results showed that line intensities clearly depend on total pressure. However, pressure has less influence on the half-widths of the spectral lines. For the retrieval computation code, further information is required to determine if the gas is opaque in this spectral region and for the different optical paths.

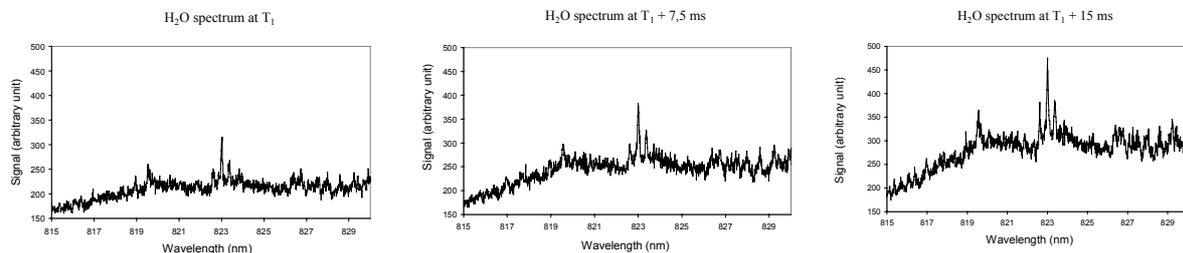


Fig. 3 : Influence of pressure on water line profiles.

Although the HITEMP database is not experimentally validated at pressures higher than one atmosphere, we have simulated  $H_2O$  line profiles under the following conditions : 2000 K, a 600 mm gas thickness, and 31 % of water at 10 and 20 bar (Fig. 4).

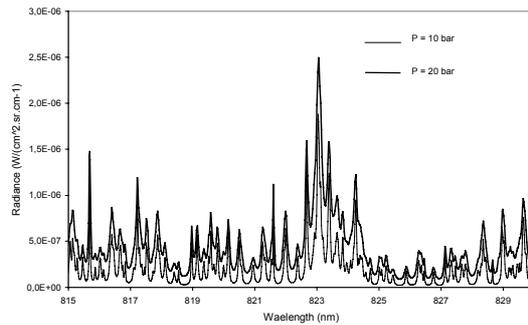


Fig. 4 : Influence of pressure on simulated water line profiles.

In these simulated spectra, we have located the same line series than in experiments. Therefore extrapolations from the spectroscopic database gave similar results than our initial experimental ones.

#### 4. CONCLUSIONS

We designed a high pressure chamber to study radiative properties of water vapor produced during combustion of a reactive stoichiometric hydrogen-air mixture at high temperature and pressure. The experimental set up is efficient and dynamic pressures were recorded up to 80 bar at the end of the explosion with a 2 % relative precision. Emission measurements of H<sub>2</sub>O were performed in the 815-830 nm spectral region using a high resolution grating spectrometer with 0.633 nm/mm linear dispersion at 800 nm. In this range, the line widths are not very sensitive to total pressure. We can obtain detailed information of H<sub>2</sub>O spectral lines at any pressure that should be very helpful for the retrieval method to determine temperature profiles into combustion processes. We will shortly extend our measurements to combustion of a reactive H<sub>2</sub>-O<sub>2</sub> mixture and compare the spectroscopic measurements for these two mixtures and characterize their thermodynamic properties.

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