CARS Measurements at high pressure in a CH_4/O_2 jet flame

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Abstract

Temperature fields in a combustion chamber fed with gaseous methane and oxygen were investigated on the Mascotte test rig of Onera. The measurements were performed with two CARS systems used simultaneously to probe both hydrogen and water vapor in the whole flowfield, at 1 MPa for two different mixture ratios (O/F). Good agreement was obtained between the temperatures profiles deduced from the H_2 and the H_2O CARS spectra, with high validation rates (ratio of spectra successfully processed compared to the total number of laser shots) for both. These results provide quantitative data which can be used for validation of CFD codes.

1. Introduction

Temperature fields in a single element combustor fed with gaseous oxygen and gaseous methane were investigated using CARS (Coherent Anti-Stokes Raman Spectroscopy) thermometry on the Mascotte test rig of Onera [1], [2] in the framework of the European program ISP-1 (In Space Propulsion) [3]. This program is devoted to the study and improvement of knowledge of technologies needed to develop a rocket engine working with liquid oxygen and liquid methane for various space applications. The item which is addressed here corresponds to oxygen/methane combustion at high pressure. Motivation of this work consists in the acquisition of an experimental data base for future validation of numerical models and computer codes.

2. Description of the test facility and of the combustor

2.1. Mascotte, version V05

The cryogenic test facility called Mascotte was developed by Onera to study the different elementary processes such as atomization, droplets vaporization, turbulent combustion... which are involved in the combustion of cryogenic propellants, usually liquid oxygen (LOX) and gaseous hydrogen. Mascotte is aimed at feeding a single element combustor with actual propellants. Five successive versions of this test facility were built up, each one representing a new step towards operating conditions closer to actual rocket engines. Version V04 consisted of adapting the bench to the study of LOX/methane combustion, a new propellants combination which is a candidate for future reusable launch vehicles. The fuel feed line comprises a heat exchanger which was designed to continuously cool a mass flow rate of 100 g/s of hydrogen from the ambient temperature to 100 K during a test duration of 30 s. This exchanger is powerful enough to liquefy the methane at the maximum requested mass flow rate of 250 g/s, well suited for investigations of gas generator type operating conditions: injection of liquid methane together with liquid oxygen. This ability will be operated in the second set of the ISP program tests, foreseen in 2011 and 2012. In the first set however, only gaseous propellants at room temperature were injected, which was possible thanks to the fifth extension of Mascotte. The latter indeed consisted of adding a gaseous oxygen line, while all the previous versions were exclusively devoted to the injection of liquid oxygen.

Figure 1 shows the Mascotte V05 operating domain around 1 MPa, in the gaseous oxygen - gaseous methane mass flow rates plane. The isobaric lines are determined for a nozzle throat diameter of 12 mm. The iso-J lines, where J is the momentum flux ratio $J = \rho V^2_{CH4}/\rho V^2_{O2}$, are computed for a classical coaxial injector with the following dimensions (LOX post inner diameter Dl=5 mm, LOX post outer diameter Dn = 5.6 mm, CH_4 sleeve outer diameter Dg = 9 mm) and both propellants injected at room temperature (288 K assumed). The two operating points corresponding to the mixture ratios M=1 and M=2 and the theoretical pressure of 1 MPa were retained for this campaign. They are also indicated on the diagram.

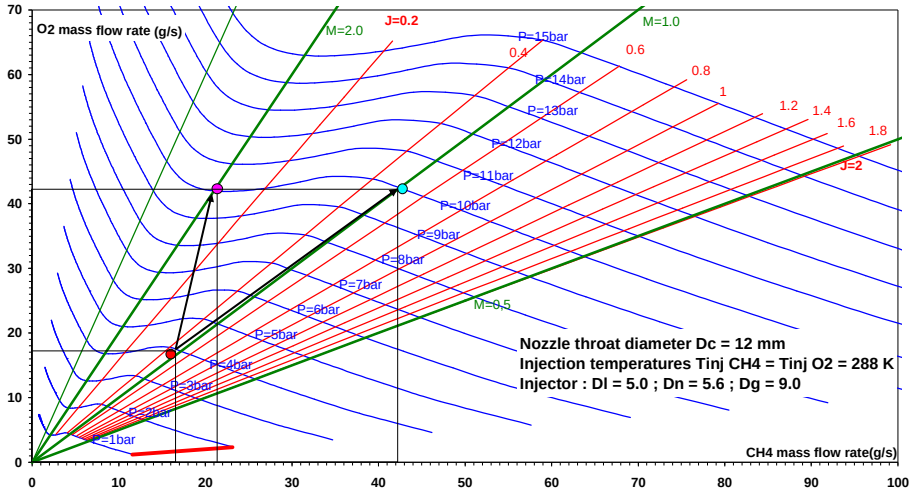


Figure 1 – Mascotte V05 domain around 1 MPa

2.2. The high pressure combustor BHP

A combustor adapted to high pressure operation was developed together with the third version of Mascotte. It is still in operation and is well adapted for the CARS temperature measurements because the visualization module is movable, so that the windows can be located at any longitudinal position between x = 0 (injector exit) and x = 400 mm (nozzle entrance). Figure 2 shows the combustor and the CARS setup around it for the three positions which were actually used in this campaign. In position 2, the probe volume is located at 65 mm downstream of the injector exit, in position 3, it is at 105 mm, and in position 5, at 210 mm. The first position was not used for CARS measurements but for OH radical imaging.

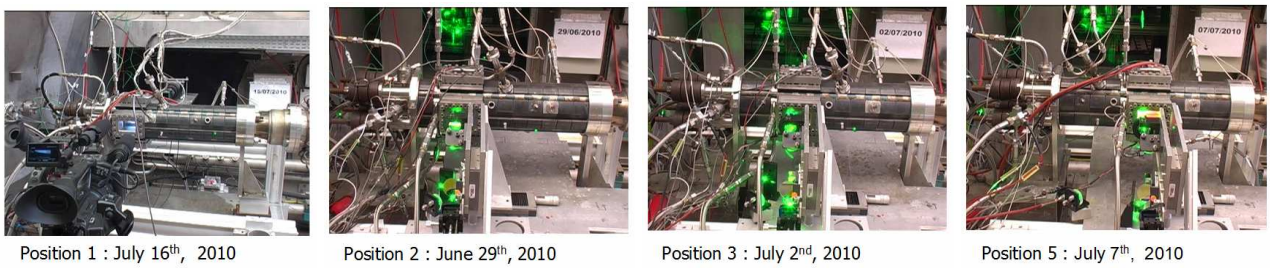


Figure 2 – CARS setup around the Mascotte combustion chamber

3. Test principle

3.1. Choice of operating points

The code *Coppelia* of Onera was used to compute the composition of the gaseous mixture at equilibrium for O_2-CH_4 combustion at 10 bar, and for mixture ratios (O/F) ranging from 0.1 to 10. Figure 4 shows the obtained mass and molar fractions of the major species: methane (CH_4), oxygen (O_2), water vapor (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen (H_2). One can see that the molar fraction of hydrogen is maximal for a mixture ratio of 1, and remains important for a mixture ratio of 2. Above 2, it decreases rapidly. As H_2 is one of the probe molecules used for CARS thermometry, this gives a second argument in favor of operating points at O/F below 2. The first argument is the thermal resistance of the combustion chamber because it is not actively cooled; it works only as a heat sink. The maximum temperature it could stand would correspond to an O/F of 3, but only for a few seconds, insufficient for CARS measurements with reasonable statistics. One has to remember that the CARS technique provides instantaneous values, and that they have to be repeated on the delay of the combustion run to obtain a statistical sampling allowing the determination of mean temperatures and standard deviation. As the repetition rate of the laser is performed at 10 Hz, at least 10 seconds of steady states are required.
The operating points retained for the CARS thermometry campaign (see table 1) differ only by the methane mass flow rate. It is reduced from 40 g/s for the mixture ratio M = 1 to 20 g/s to for the mixture ratio M = 2. The nitrogen film mass flow rate is 15 g/s in each case. These points are slightly different from the ones shown on figure 1 because the diagram was simulated without taking into account the nitrogen film used to isolate the windows from the flame front.

The experimental pressure may also be ten or even twenty percent above 1 MPa because the exact effect of the nitrogen flow is complex to predict with a 0D calculation. The result depends on the behavior of the film. If this one is destroyed via a preferential diffusion process, nitrogen is completely mixed with the combustion gases and heated. In the opposite case, nitrogen remains close to the wall at a temperature much lower than the core of the flow. And it is obvious that in the first situation, the expansion of the nitrogen produces a larger rising of the pressure than in the second case

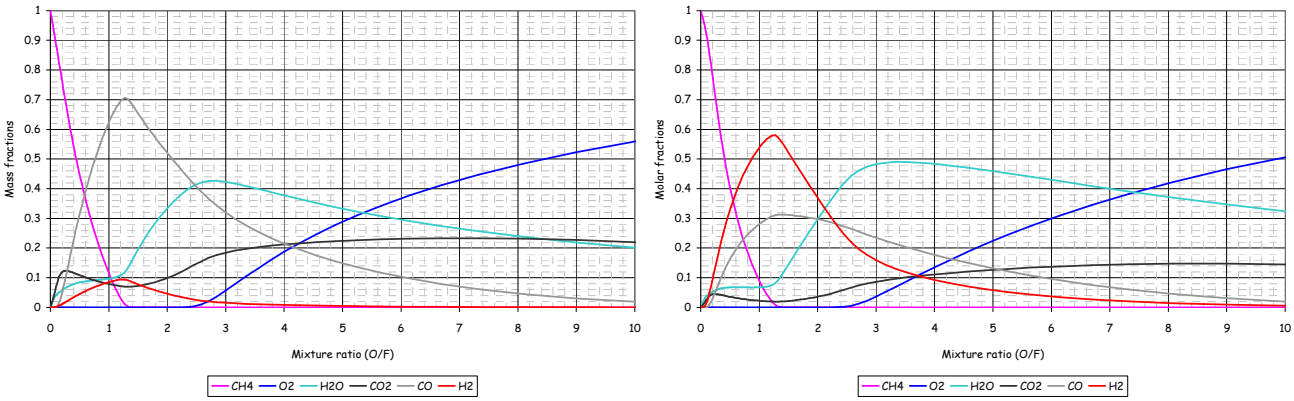


Figure 3 – Mass and molar fractions of major species at equilibrium versus mixture ratio

Table 1 – Operating points of the Mascotte CARS campaign

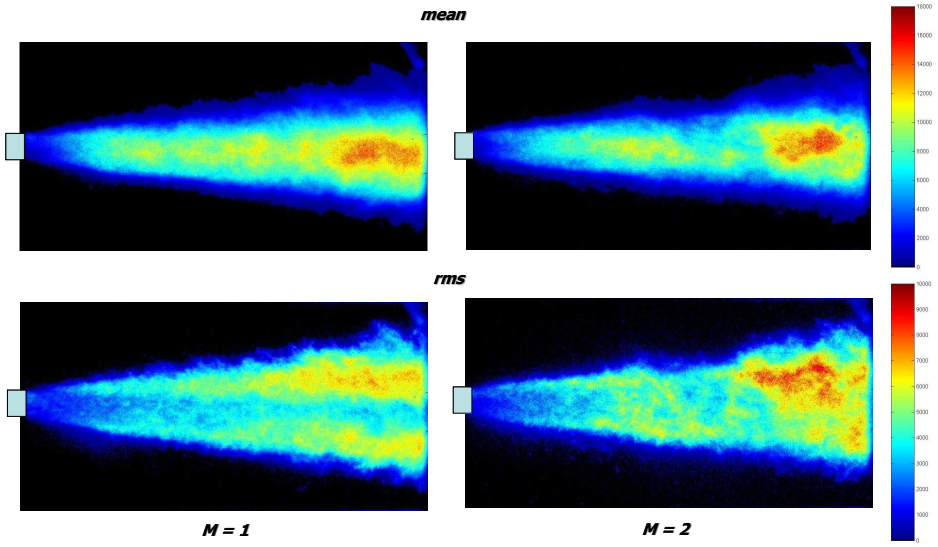
	Mixture ratio M=1	**Mixture ratio M=2**
O_2 mass flow rate	40 g/s	40 g/s
CH_4 mass flow rate	40 g/s	20 g/s
N_2 mass flow rate	15 g/s	15 g/s

3.2. OH* radical chemilumiscence imaging

Emission, i.e. chemiluminescence, of OH* radicals is used to locate regions of intense combustion. Radiation from OH takes place in the near UV range between 306 and 320 nm [5]. Emission bands are clearly separated from those of oxygen and water. Detection is achieved with an intensified ICCD or CMOS camera. In our case, we had a Princeton camera with a 16 bits depth for low speed (4 images per second) and a Photron camera for high speed (6000 frames par second) recording. Both were equipped with appropriate intensifiers and Nikon UV objectives. A UG-5 Schott glass filter blocks radiation above 400 nm and two WG 305 Schott filters suppress radiation below 283 nm while passing 306 nm and 320 nm where chemiluminescence is observed. The cameras were installed on both sides of the combustor at right angles with respect to the axis. Emission images provide the instantaneous signal integrated over the line of sight (i.e. over a line orthogonal to the axial direction). It is not possible to deduce the local values from an observation under a single viewing angle. However, the instantaneous images may be averaged and the resulting data may be processed through an Abel transform to determine the mean volumetric light intensity distribution [6]. This type of numerical tomography is suitable if the flame is assumed to be axisymmetric and if self absorption of the light radiated by the flame is not too large.
Prior to the temperature measurements, OH imaging tests were performed to provide information on the overall shape of the flame and on the mean flow structure.

Figure 4 shows that the flame shape is not much affected by the increase of the mixture ratio from 1 to 2. The images recorded with the optical windows in the first position show that the OH* emission appears in the immediate vicinity of the injector and that the flame angle is nearly the same for M=1 and M=2. Only the RMS values of the light intensity indicate that the turbulence level seems higher for M=2 than for M=1. Larger differences appear when the optical windows are in position 5. For M=1, the flame is completely closed in this region, while for M=2, a significant emission of OH* subsists at the end of the optical window. Both mean and RMS value show that the flame closure is not far from this point, but there are many instantaneous events where the flame is still present at the end of the optical window. The green dots on the images correspond to the locations of the probe volume for CARS thermometry.

Optical windows in position 1.



Optical windows in position 5.

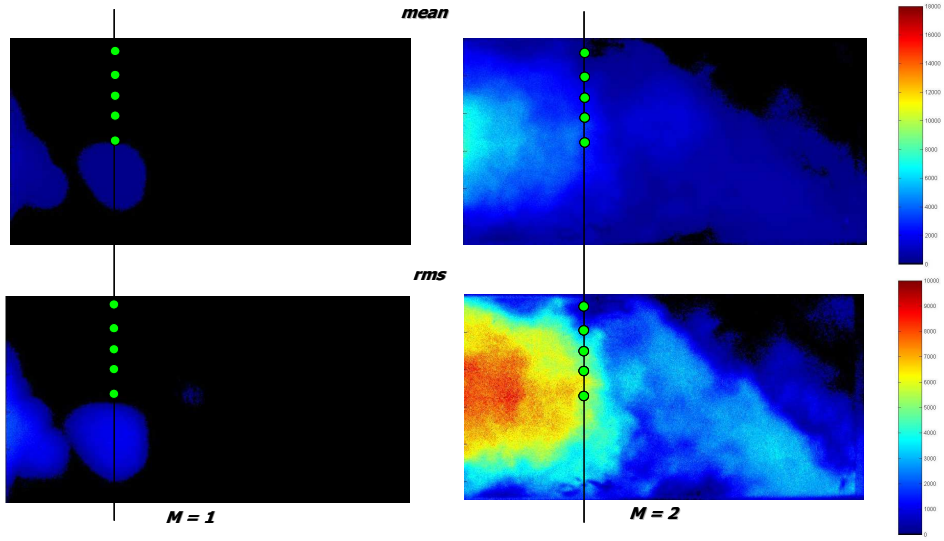


Figure 4 – Mean and RMS OH* images for mixture ratio (O/F) M=1 (left) and M=2 (right)
Optical windows in position 1 (top) and in position 5 (bottom).

3.3. CARS thermometry

Coherent anti-Stokes Raman scattering (CARS) spectroscopy of the hydrogen and water vapor molecules were widely used in the past for temperature measurements in rocket engines because these molecules are present in high concentrations in nearly all regions of LOX/GH_2 high-pressure cryogenic combustion systems [7-9]. In the present experiment, the same experimental procedure was retained. Temperature measurements were performed with two CARS systems used simultaneously to probe both hydrogen and water vapor in the whole flowfield. The first one was operated by a team of the Department of Physics of Onera, and the second one by a team of the General Physics Institute (Russian Academy of Sciences) of Moscow (actually working as a subcontractor of the DLR/ Lampoldshausen). The first optical bench comprises a frequency-doubled injection-seeded Nd:YAG laser and a broadband dye laser that generate the pump and the Stokes beams required for the multiplex CARS measurements. The Stokes laser is centered at 683 nm to excite the Q-branch of hydrogen with a 200 cm^{-1} bandwidth. The second laser bench used to probe water vapor consists of a broadband dye laser pumped by a multi-mode Nd:YAG laser. Both laser pulses are synchronized with a delay of 100 ns and a temporal jitter of 300 ns. The planar BOXCARS arrangement is used for the H_2-CARS system in which referencing is applied systematically. For the H_2O-CARS system, a USED-CARS beam geometry is used. All the beams are then combined and focused in the combustion chamber using a 160 mm focal length achromat yielding the following typical probe volume dimensions: 0.8 mm long and 100 µm diameter for the H_2-CARS, 2 mm long and 150 µm diameter for the H_2O-CARS (figure 5).

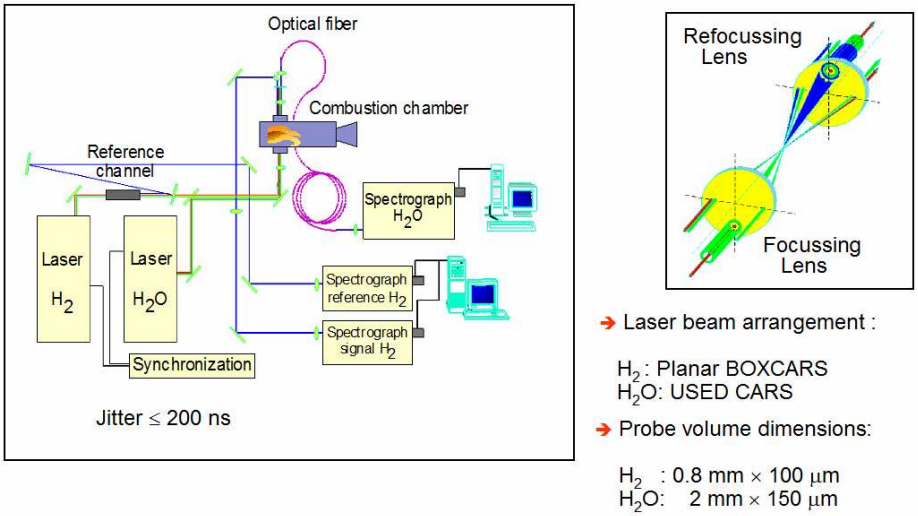


Figure 5 – Experimental set-up

For each species, a specific data processing has been developed and used to reduce CARS spectra to useful temperature despite the lack of knowledge on the mixture composition in the probe volume. A library of pre-calculated theoretical spectra was generated at 50 K increments over a range encompassing the expected flame temperature. Libraries were calculated for various molar fractions of H_2 and H_2O in order to characterize the effect of the linewidths on the resulting CARS spectral shape. The temperatures were evaluated by a weighted least squares method of the measured CARS spectra with the theoretical spectra. The accuracy of the temperature is assumed to be equal to 10 % for both CARS spectra. In the same time, the H_2O molar fraction is deduced from the ratio between the resonant part and the non resonant of the H_2O CARS spectra.

4. CARS thermometry results

The CARS measurements were carried-out for two experimental conditions (chamber pressure of 1 MPa, mixture ratios O/F of 1 and 2) and for three axial locations: positions 2, 3 and 5 of the combustor module with optical ports, (figure 2), which correspond to downstream distances x = 65 mm, x = 105 mm and x = 210 mm from the injection plane. Five radial distances were investigated for each profile: y = 0 (on the flow axis), y = 5 mm, y = 9 mm, y = 13 mm and y = 16.5 mm. An ensemble of 150 instantaneous temperature measurements was recorded during each run with an uncertainty of 100 K. However the temperature fluctuations induced by turbulent combustion exceed by far this uncertainty. The measurements also show no evidence of a temperature evolution during the run indicating that the process is stationary and that it may be characterized by histograms, mean values and standard deviations. Thus, figure 6 shows typical data obtained at 210 mm from the injector, displayed with a temperature step of 100 K matching the apparatus uncertainty. The temperature distributions display the degree of burnout which depends primarily on the mixing of CH_4 and O_2.

Depending on the measurement locations, the validation percentage, defined as the ratio between the number of spectra successfully processed and the total number of laser pulses, ranges between 0 and 100 %. Data processing fails when the experimental signals are too weak reflecting either low instantaneous species concentration of the probe molecule (H_2 or H_2O) within the probe volume or beam steering effect due to large refractive index gradients present in the combustion chamber.
The mean temperature increases downstream from the injector (figure 7). The radial profiles are relatively flat, which is not surprising at x = 210 mm where the flame is closed. Closer to the injector, no peak temperature characteristic of the presence of the flame front is visible. The reason of this result comes from the inadequacy of the CARS technique allowing single point measurements and the fineness of the flame front which requires, for its detection, the acquisition of many single point measurements with a very good spatial resolution. Unfortunately, for each location downstream from the injector, the temperature measurements are only performed on five locations in the radial direction, leading then to a weak probability to have one of them precisely in the reaction zone. High validation rates and low standard deviations mean that the mixture is quite homogeneous. Conversely, low validation percentages and large temperature standard deviations would show the presence of a region where species concentration of the probe molecule and temperature fluctuate, demonstrating the presence of an unsteady mixing layer between the inner oxygen jet and the surrounding methane flow.

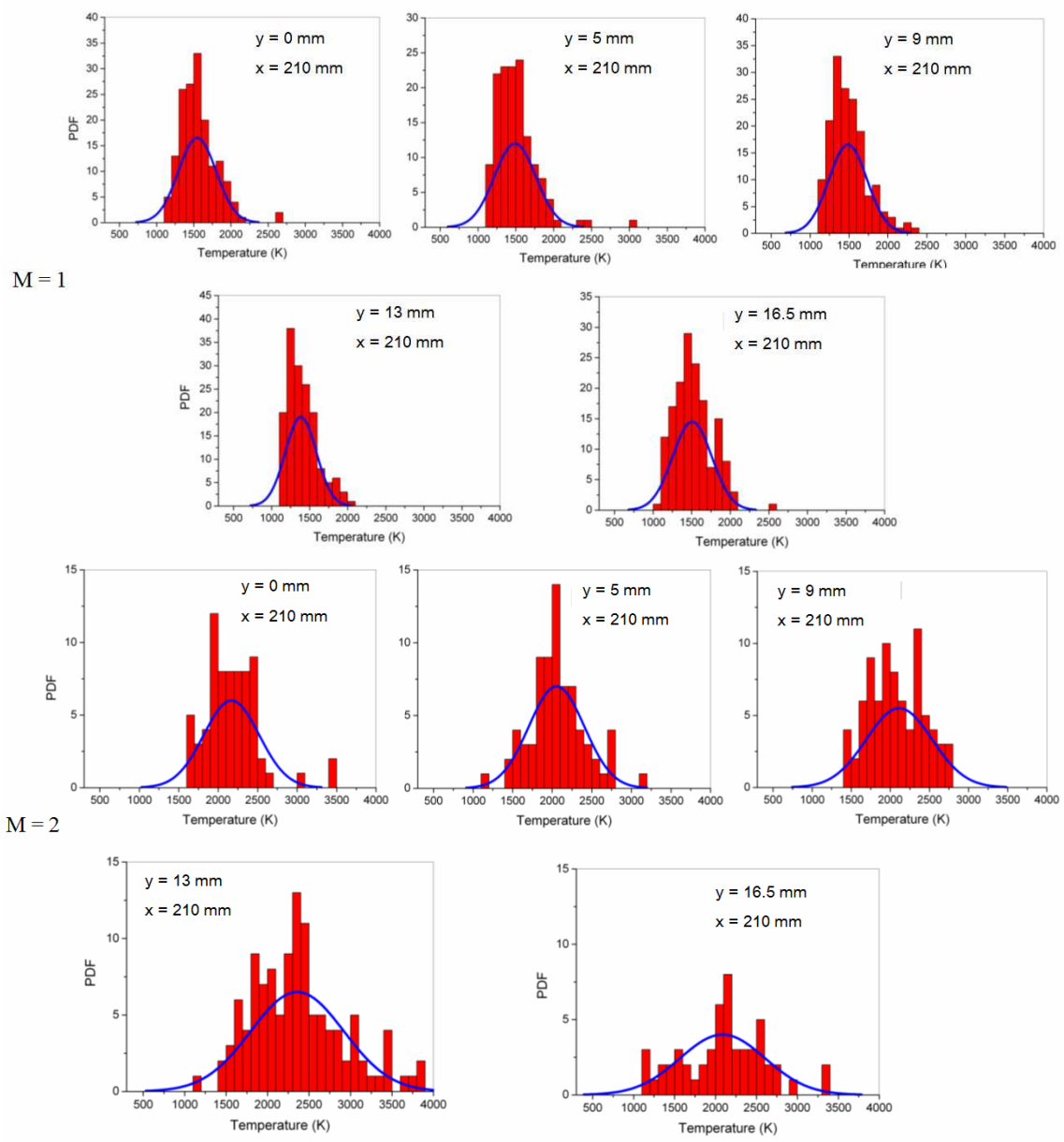


Figure 6 – Temperature histograms obtained with H_2 CARS spectra at 210 mm from the injector

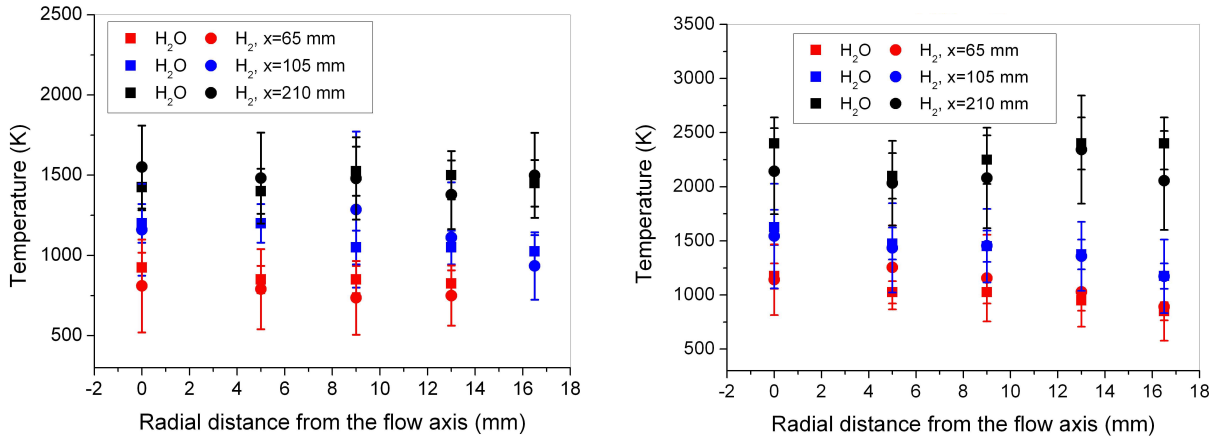


Figure 7 – Temperature profiles deduced from H_2 and H_2O CARS spectra at three distances downstream from the injector for mixture ratio M=1 (left) and M=2 (right)

4. Comparison between experimental and numerical temperature fields

First numerical simulations of the combustor, operating at the mixture ratio M=1 and M=2, were achieved using a k-ω SST turbulence model [10] with a turbulent Schmidt number equal to 0.7. The combustion model used was *TPaSR* (Transported Partially Stirred Reactor) with the 4-steps global kinetics mechanism from Jones & Lindstedt [11]. The principle of this combustion modeling is a competition between turbulent mixing and kinetic reaction: O_2 is injected as a different species, O_2bm ("b"efore "m"ixing) and a « mixed is burnt » model is applied to « activate » O_2bm (time scale = turbulent time scale) when mixed with CH_4. Then, O_2 can burn following the kinetic mechanism. This is only applied to O_2bm since this is the default species and it is injected at the center of the domain. The overall kinetic mechanism used is then: O_2bm + CH_4 => O2 + CH_4 ; 0.5 O_2 + CH_4 => CO + 2 H_2 ; CH_4 + H_2O => CO + 3 H_2 ; H_2 + 0.5 O_2 <=> H_2O ; CO + H_2O <=> CO_2 + H_2 .

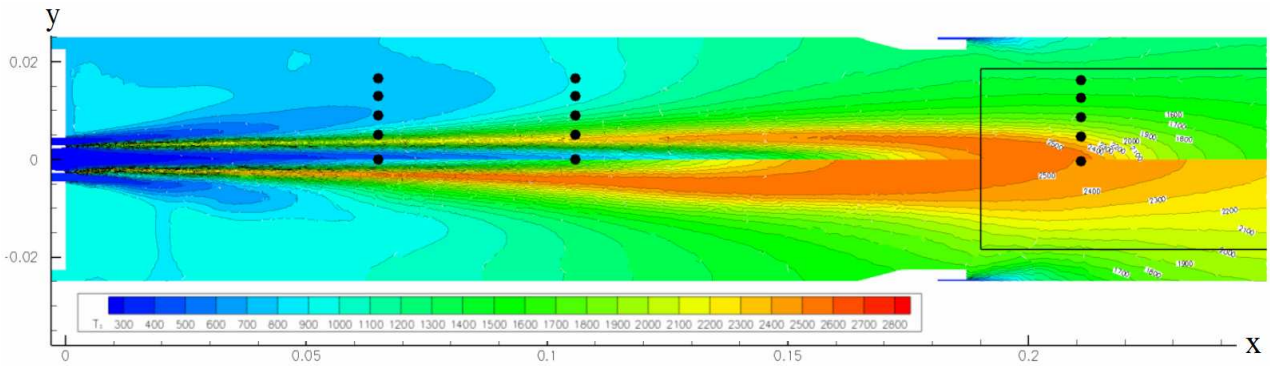


Figure 8 – Computed temperature field for M=1 (up) and M=2 (down)

The temperature values obtained numerically and plotted in figure 8 are not yet satisfying. The locations of the CARS measurements points, as well as the window position, are shown on figure 8. For example at x = 210 mm, the experimental temperature profile is flat, around 1500 K, while the computation shows that this location corresponds to the closure zone of the flame. A maximum temperature around 2500 K (orange) is expected on the axis with a rapid decrease at the edge of the flame. Outside of the flame, the expected temperature is between 1400 and 1600 K (green), in agreement with the experimental values. The numerical temperature profiles extracted from Figure 8 are plotted in Figure 9, to be compared with Figure 7. Numerical results show very sharp gradients in the temperature field. These variations are maybe not detected by the CARS measurements because of the limited spatial resolution, but they can also be overestimated by the computation. Besides, the CARS technique measures the temperature of one molecule which has to be locally detected for evaluating the temperature, thus the experimental temperature profile is characteristic of zone where H_2 / H_2O molecules are spatially and temporally present. Since this computation is stationary, there are zones in the domain of simulation where no molecule of H_2 and H_2O are present while the true physical behavior of the burning flow evidently contains unsteady bursts of mixed gases containing these molecules.

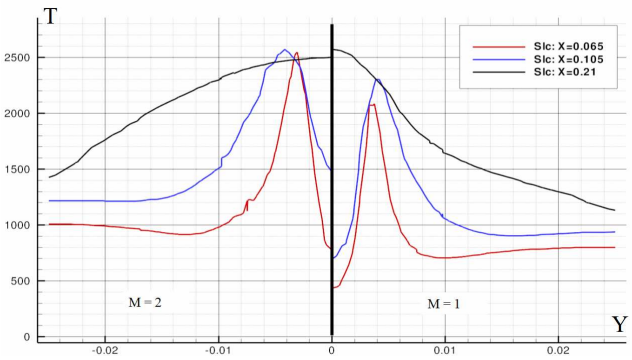


Figure 9 - Numerical temperature profiles

Since the OH* radical is not computed in the present work, it is not possible to compare directly the OH* concentration fields with the images of chemiluminescence. Nevertheless some remarks can be made on the temperature field of figure 8. In accordance with experimental data, the high temperature zone is longer and thicker for the mixture ratio M=2. However, the flame seems to be quite too long for both computations. In Figure 10 the heat release is shown for both simulations (along with the geometry). This physical parameter is useful to interpret the

OH* emission images since it shows the region of intense chemical reactions. The “opening” of the heat release for M=2 is not due to the main reaction between O_2 and CH_4 since O_2 is already consumed, but is due to the other chemical reactions of the kinetic mechanism, particularly $CH_4+H_2O \Rightarrow CO+3H_2$. This chemical reaction seems to occur later for the M=1 case.

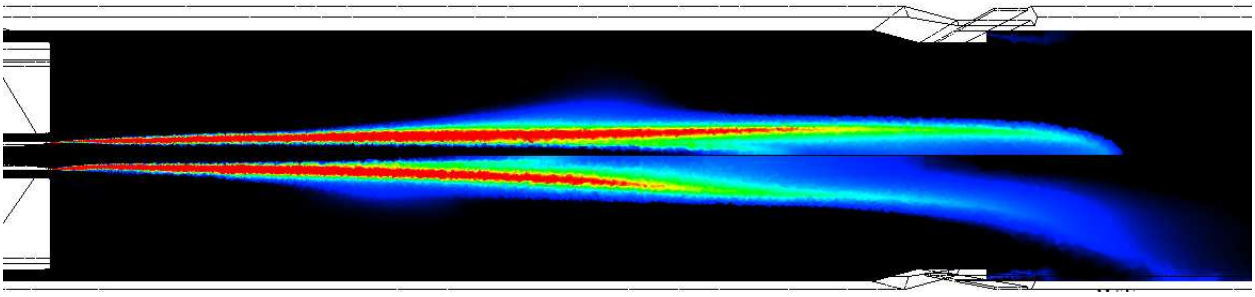


Figure 10 - Heat Release for both M=1 (up) and M=2 (down) cases

5. Conclusion

Temperature fields in a combustion chamber fed with gaseous methane and oxygen were investigated using CARS thermometry on the Mascotte test rig of Onera in the framework of the European project ISP-1 on in space propulsion. The measurements were performed with two CARS systems used simultaneously to probe both hydrogen and water vapor in the whole flowfield. Measurements were performed at 10 bar (1 MPa). An ensemble of about 150 instantaneous measurements was recorded during each run of the burner, for the different operating points of interest, defined by the pressure and mixture ratio (O/F).

The temperature distributions display the degree of burnout which depends primarily on the mixing of H_2 and H_2O. Agreement between the temperatures profiles deduced from the H_2 and the H_2O CARS spectra, in terms of the mean and the standard deviations, is good. The high validation rates, defined as the ratio between the number of spectra successfully processed and the total number of laser shots, highlight the interest to use CARS in these severe conditions. Analyzing the complete set of data provides an insight of the flame structure which delivers a high level of turbulence as indicated by the standard deviation of the instantaneous temperatures.

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