



HAL
open science

KHz Rate Fs/Ps-CARS Thermometry For Supersonic H₂/Air Combustion Studies

Clément Pivard, Michael Scherman, Rosa Santagata, Guillaume Pilla,
Guillaume Pelletier, Thomas Le Pichon

► **To cite this version:**

Clément Pivard, Michael Scherman, Rosa Santagata, Guillaume Pilla, Guillaume Pelletier, et al..
KHz Rate Fs/Ps-CARS Thermometry For Supersonic H₂/Air Combustion Studies. 21st LISBON
Symposium, Jul 2024, Lisbon, Portugal. 10.55037/lxaser.21st.181 . hal-04734703

HAL Id: hal-04734703

<https://hal.science/hal-04734703v1>

Submitted on 14 Oct 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

kHz rate fs/ps-CARS thermometry for supersonic H₂/air combustion studies

C. Pivard^{1,*}, M. Scherman^{1,*}, R. Santagata¹, Guillaume Pilla², Guillaume Pelletier², Thomas Le Pichon²

1: ONERA, Physics Instrumentation Environment Space Department, 6, Chemin de la Vauve aux Granges - 91123 PALAISEAU, France

2 : ONERA, Multiphysics for Energetic Department, 6, Chemin de la Vauve aux Granges - 91123 PALAISEAU, France

* Correspondent authors: [*Michael.scherman@onera.fr](mailto:Michael.scherman@onera.fr), clement.pivard@onera.fr

Keywords: Coherent Raman Spectroscopy, Thermometry, Supersonic Combustion

ABSTRACT

Accurate flow field measurements are essential to probe the phenomena involved in aeronautical engines undergoing high temperature and high turbulences. Indeed, reliable experimental datasets are needed to compare and validate numerical models. Among other laser diagnostics, Coherent Anti-stokes Raman Scattering (CARS) [1,2] is a well-established non-linear spectroscopic technique used to probe harsh environments, since it provides non-intrusive local point measurements of chemical composition and temperature.

We report here hybrid fs/ps Coherent Anti-Stokes Raman Scattering (fs/ps-CARS) thermometry campaign performed on N₂ in a supersonic H₂/air combustion. We used a mobile and compact laser architecture that shapes, synchronize and generates the laser beams necessary for CARS spectroscopy. The instrument was moved to a large-scale facility representative of a scramjet combustor (ONERA LAERTE/LAPCAT-II bench). H₂/air was injected during several burst at 0,12 and 0,15 equivalent ratios. Using kHz single-shot measurements combined with motorized translation stages, spatial and temporal resolution were obtained to probe the flow and the combustion at various positions upstream and downstream the hydrogen injectors. At these positions, horizontal and vertical temperature profiles were retrieved and compared with a numerical unsteady fluid dynamic simulation using delayed detached eddy simulations (DDES) developed at ONERA (CEDRE). The position of the combustion inside the combustion chamber could be identified through several horizontal and vertical profile temperature measurements. The signal-to-noise ratio of the detection was optimized by empirically adjusting the number of averaged laser shots based on the level of flow turbulence. For instance, far downstream the H₂ injection, averaging over 10 to 100 pulses was possible as the heated air flow was steady. This was confirmed by the good agreement with numerical simulations although some distortion could still be observed and will be used to adjust the numerical simulation algorithm. However, averaging was no longer possible close to the injectors, where a highly turbulent H₂/air combustion was observed. Nevertheless, taking advantages of the high rate single-shot capacity of the spectroscopic technique, temperature could still be retrieved inside this area. These measurements provided a valuable experimental database for comparing and refining computational fluid dynamics modeling.

1. Introduction

Precise and robust measurement methods are needed to probe the complex and reactive media met in aeronautical engines. Indeed, experimental data acquired in representative test benches provide a necessary database to improve and validate the numerical models describing the thermo-fluid dynamics inside the combustion chamber. However, probing these complex reactive flows can be challenging as high temperature, due to high spatial gradients and temporal fluctuations present in these turbulent flows. Therefore, a noninvasive high rate single-shot measurement in a relatively small probe volume seems necessary.

Coherent anti-Stokes Raman Scattering (CARS) [2] spectroscopy allows to probe the ro-vibrational molecular transition levels which provides accurate information of the local probed medium such as the relative concentration or temperature. It has been particularly used to measure temperature of major species of complex molecular media in harsh environments [5-7-8-10]. CARS measurements indeed provide a strong signal level, unmatched temporal resolution, and good precision in single-shot and at high repetition rate [1,8].

In this paper we present the results of an experimental CARS thermometry campaign on a H₂/air supersonic combustor (ONERA combustion LAERTE/LAPCAT-II bench) representative of a scramjet. The temperatures were obtained from the fitting of a Boltzmann law on the N₂ Q-branch ro-vibrational lines. These temperature measurements were performed at a repetition rate between 10 Hz and 1 kHz depending on the camera integration time.

2. Experimental laser system

CARS spectroscopy is a non-linear four-wave mixing process where two beams, named “pump” and “Stokes”, are used to excite the macroscopic molecular ro-vibrational coherences. These coherences Ω are excited when the two excitation frequencies ω_p and ω_s match a Raman active vibration such as $\omega_p - \omega_s = \Omega$. A third laser beam ω_{pr} , the “probe”, interrogates the coherences which results in the generation of a collimated blue-shifted anti-Stokes signal that satisfies the energy conservation $\omega_{AS} = \omega_{pr} + \Omega$ and the phase matching rule. The detection becomes therefore immune to fluorescence emission. The anti-Stokes spectrum provides information on the thermodynamic properties of the medium such as temperature, pressure and relative concentrations of the major species.

In the hybrid fs/ps regime, the femtosecond pump and Stokes pulses provide high peak power and a broadband excitation while the picosecond probe pulse offers highly resolved CARS spectra. This combination is well-suited for single-shot measurements at a high repetition rate [4].

Our unique fs/ps-CARS laser source [9] is able to generate, synchronize and shape the laser pulses in a compact and mobile structure. A picture of the laser system and the mobile detection system are presented in Figure 1-(a) and a schematic of the CARS system is showed in Figure 1-(b).

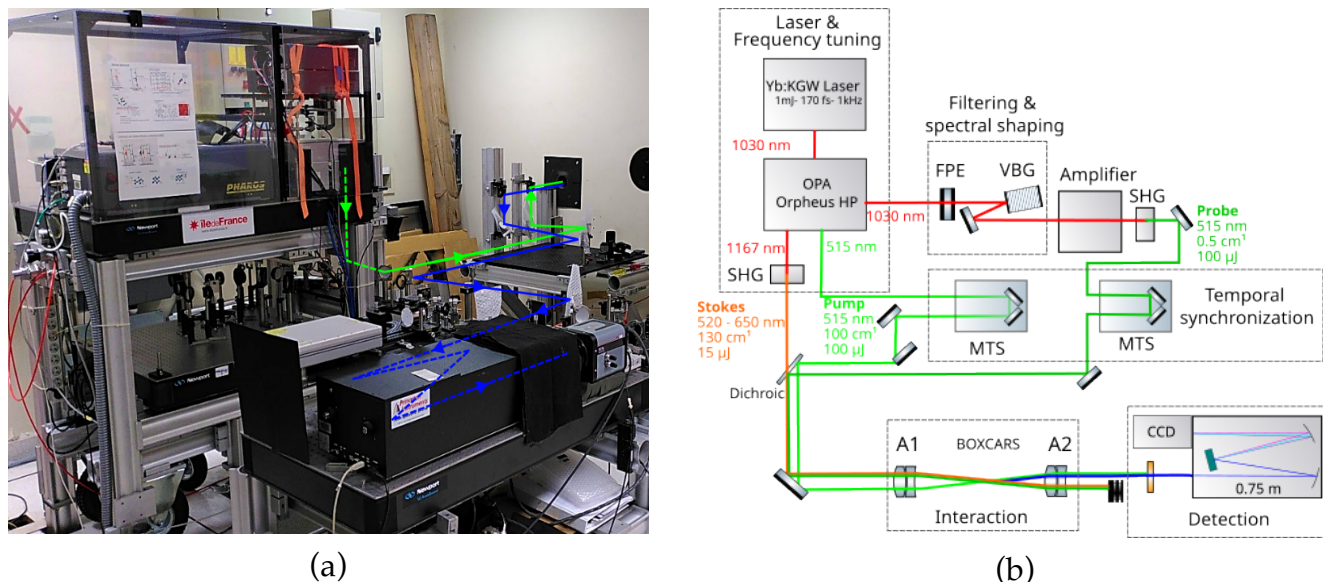


Figure. 1 (a) CARS laser and detection system placed in an optical room beside the combustion chamber room. The laser and detection benches systems are both independent and transportable. (b) Schematic of the generation and synchronization of the three laser beams and detection system, see Ref [9].

The laser system is composed of a Yb:KGW laser source (Pharos Lightconversion) emitting a 1 kHz train of 1 mJ pulses at 1030 nm (175 fs) pulses that pumps an optical parametric amplifier (OPA, Orpheus, Lightconversion). The Stokes beam is generated from the second harmonic of the idler radiation emitted by the OPA. The Stokes wavelength can be tuned to excite a specific molecular transition ($\lambda_{St} = 580 \text{ nm}$ for N₂ Q-branch). The 515 nm Pump beam is obtained from the residual of a second harmonic beam used in the OPA module. The residual of the 1030 radiation is spectrally filtered, amplified, and frequency doubled to generate the probe beam. The probe spectrum is indeed first filtered and shaped to obtain a narrowband emission using a volume Bragg grating combined with a Fabry-Perot etalon. As this process is energy costly, it is then needed to amplify the laser beam to obtain sufficient energy to perform single-shot measurements. A diode pumped commercial amplification module (Taranis, FiberCryst) then increases the pulse energy before second harmonic generation. This provides 58 ps duration pulse train at 515 nm with 100 μJ per pulse.

The temporal synchronization is performed using two motorized translation stages set on the probe and pump beam. The three laser beams are then recombined using dichroic mirror and

focused into a BOXCARS arrangement [3] using an achromatic spherical lens. The measurement volume, corresponding to the superposition of the three laser beams, has a cylindrical-like shape, of approximately 0.1 mm in diameter and 1.5 mm long. The anti-Stokes beam is isolated with a filter before being analyzed using a grating spectrometer (ACTON, Teledyne) coupled with an EMCCD camera (ProEM, Teledyne).

Temperature was estimated by fitting a Boltzmann law on the experimental N₂ Q-branch CARS spectra [1,4]. The spectral excitation profile was obtained by recording pure non-resonant responses in the chamber filled with Argon gas. Typical 100-shot averaged anti-stokes spectra obtained in heated air and in the burning gases during the combustion inside the LAPCAT chamber are showed in Figure 2. In heated air (Figure 2 (a)) the first vibrational band is the only one populated while in the flame (Figure 2 (b)) three vibrational bands can be clearly observed

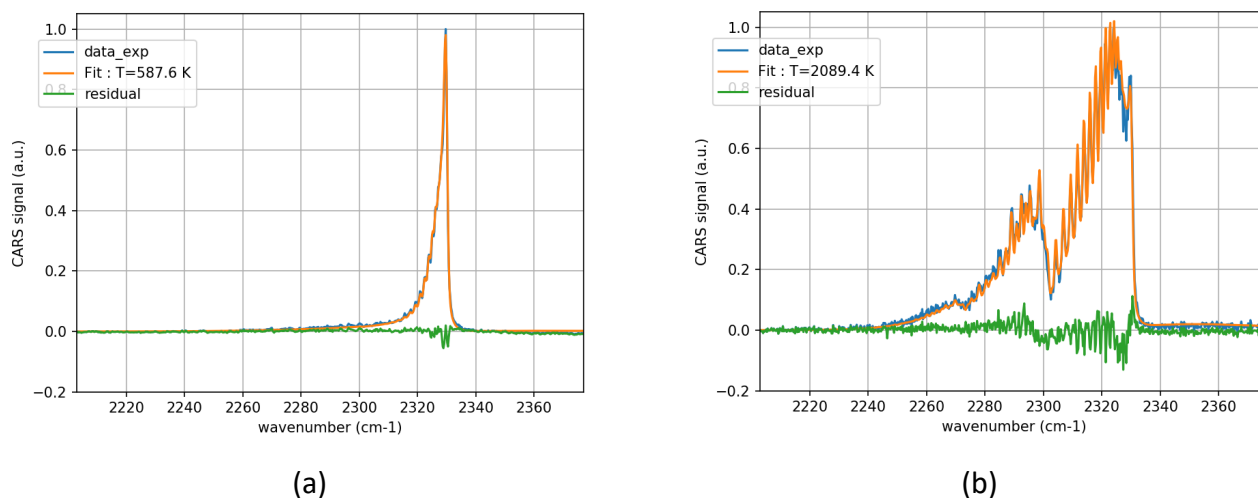


Figure 2 Typical experimental CARS spectrum obtained at (a) in heated air at 587 K and (b) in the burned gases at 2089 K. Simulated N₂-CARS spectrum fitted (orange line) on experimental data (blue line) and residual (green line).

One of the challenges is to maintain a high enough CARS signal-to-noise ratio (SNR) at high temperature. As the temperature increases, the gas density decreases and the spectral rovibrational transition level distribution spreads over a broader spectral range leading to a global diminution of the signal. This results in lower precision in the measured temperature. A solution to increase the SNR at high temperature is to average the temperature over several pulses. This approach was used in this campaign in zones where the temperature was observed to be enough steady, like in the burnt gases far downstream from the combustors. This strategy could not be used in locations exhibiting turbulent behavior, like at the vicinity of the injectors, where single shot measurements were performed even if SNR was significantly reduced.

3. LAPCAT-II supersonic H₂/air combustor

The CARS laser system was implemented at the ONERA LAERTE/LAPCAT-II bench test representative of a scramjet combustor (Figure 3.a). CARS measurements were performed in supersonic H₂/air combustion at equivalence ratios of 0.12 and 0.15. In this facility, the air flow is first preheated using two hydrogen preheater stages allowing to increase the temperature to 1700 K. This hot flow is then accelerated up to Mach 2 speed through a Laval nozzle. Hydrogen is then injected through two sonic opposite jet-in cross flow injectors, located at the top and bottom walls of the test section. This operating strategy allows an effective combustion sequence of 5 seconds. CARS signal was recorded while a motorized stage was translated in order to scan the measurement volume inside the chamber. Horizontal and vertical scans were performed during the combustion sequence at various positions downstream the injectors.

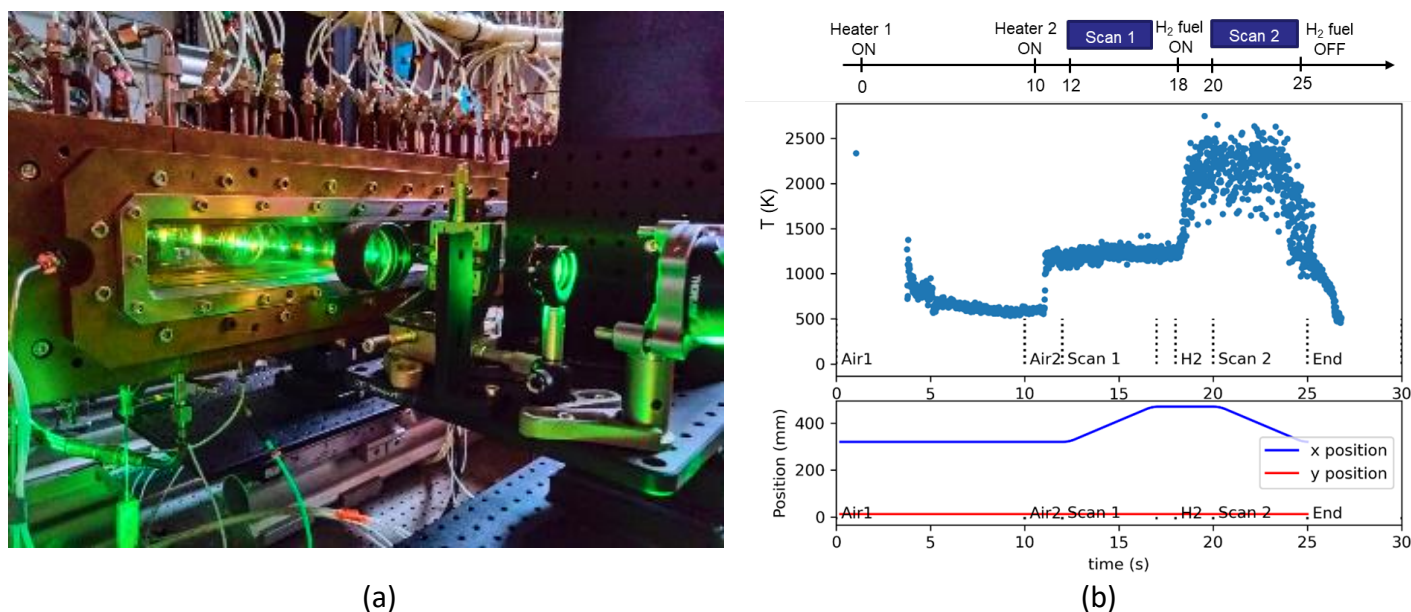


Figure 3 CARS diagnostics performed in the combustion chamber of the LAERTE facility with optics mounted on motorized translation stages to scan the measurement volume. b) Typical measurement sequences showed in time. First two stages of preheating are started, two scans are performed: one without combustion and one with H₂ combustion.

A typical experimental sequence is presented in Figure 3 (b). The experiment starts with two steps of preheating ($t \sim 5$ s and $t \sim 12$ s) before the injection of hydrogen starts ($t \sim 19$ s). Two 5 s-duration spatial scan are performed using x-y motorized translation platform synchronized with the burst: the first one when the non-reacting heated air flow is stabilized, and the second one after the hydrogen injection when the combustion reach stable conditions. Typical horizontal and vertical

positions of the profiles scanned during the burst are shown in Figure 4 and labelled from S0 to S6. The EMCCD camera is triggered at kHz rate with the laser pulses emission and starts acquiring at the beginning of the test sequence.

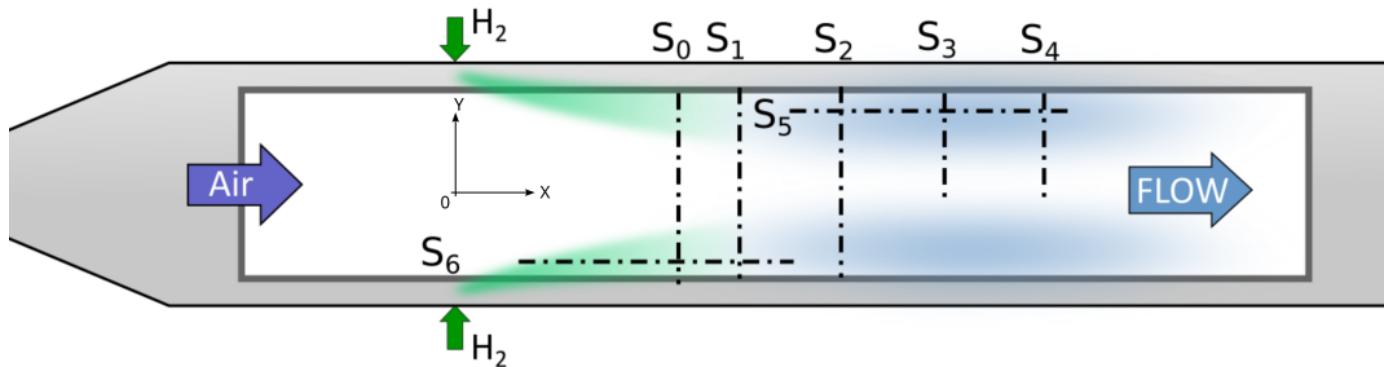


Figure. 4 Representation of the combustion chamber from a sideview, where in black dashed lines are represented typical vertical and horizontal scans of the measurement volume inside the chamber (S0 to S6).

4. Results

N_2 CARS spectra were acquired at 10 Hz (100-shot averaging), 100 Hz (10-shot averaging) and 1 kHz (single shot) rate based on the flow turbulence to optimize, when possible, the detection SNR. Experimental data were compared to 3D numerical unsteady fluid dynamic simulations using delayed detached eddy simulations (DDES) using the inhouse CFD 3D-algorithme CEDRE [6]. Vertical scans performed on half of the window's height, due to the symmetry of the flow, were acquired far downstream from the H_2 injection at 200 mm (vertical scan S3) and 250 mm (vertical scan S4) from the injectors (Figure 5). At this location, the temperature appears rather steady as most of the flow is composed of burnt gases. Therefore, laser pulses could be integrated over 10 to 100 shots on the CCD camera to increase the SNR of the CARS spectra. As showed in Figure 5, the experimental CARS temperature measurements show similar profiles to the numerical simulations, with a cold flow in the middle of the chamber and hot gases on the high edge of the combustor. At low equivalence ratio ($\phi=0.12$, Figure 5 (a)) a good agreement is observed between the mean experimental temperature values and the simulation, whereas at higher equivalence ratio ($\phi=0.15$, Figure 5 (b)), the position and size of the combustion zones appears to be slightly misestimated by the simulation as well as the burnt gases temperature. Still, these set of data provide good information to improve or calibrate the simulations with the current experience.

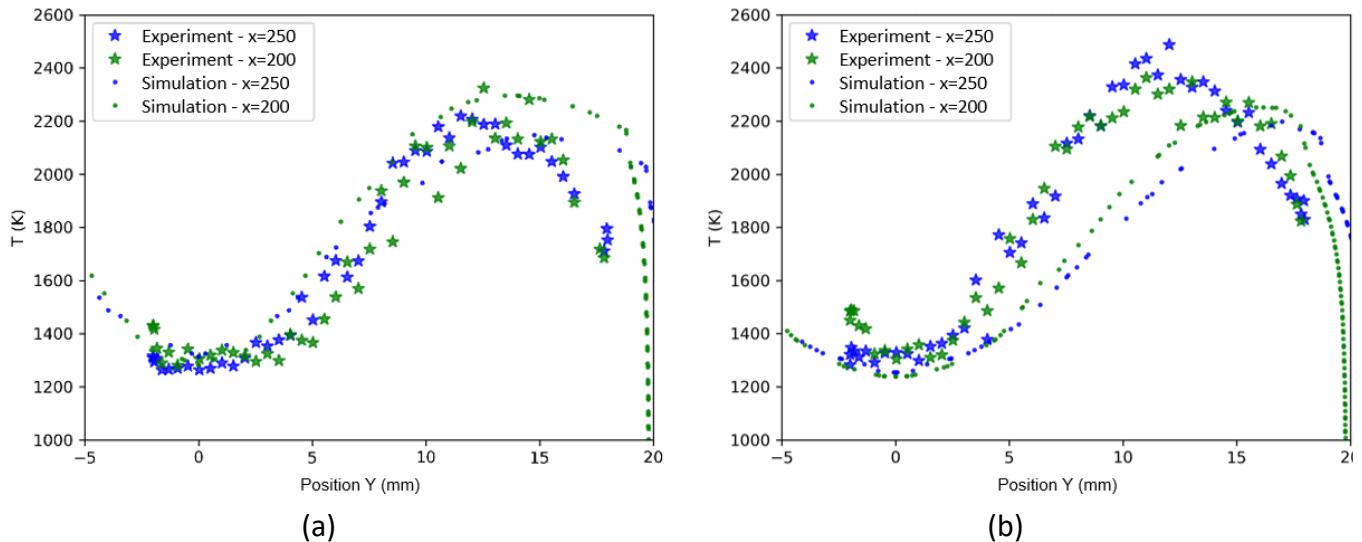


Figure. 5 Experimental temperature measurements (stars) versus height (y , vertical scan) at two horizontal positions (scan S3 in green at 200 mm downstream the injector, and scan S4 in blue at 250 mm) compared with numerical model (dots) at (a) 0.12 and (b) 0.15 H₂/air equivalence ratio.

As the fluctuations increase closer to the reaction zone at 160 mm downstream the injector (vertical scan S2) the acquisition rate was increased to 100 Hz (10 shots averaging). The combustion was probed for $\phi=0.12$ and $\phi=0.15$ H₂/air equivalent ratio as shown in Figure 6. The two combustion zones, on the high and low edge of the chamber, can still be distinguished very clearly despite the presence of high temperature variations in these zones. These high temperature variations are the signature of a turbulent flow with high temperature temporal gradient and non-stable flame front position. However relatively good agreement is observed with the numerical simulations although a discrepancy can be observed in the flame height which is slightly overestimated for $\phi=0.15$. It can be noticed that at higher H₂/air equivalent ratio, the temperature profile is shifted towards the center of the chamber (lower values of Y position) with higher measured temperature. Indeed, as the equivalent ratio increases, the flow rate and linear momentum between the main flow and the injection also increases. This enhances jet penetration and stabilizes gas mixing closer to the chamber's center, positioning the flame nearer to the center.

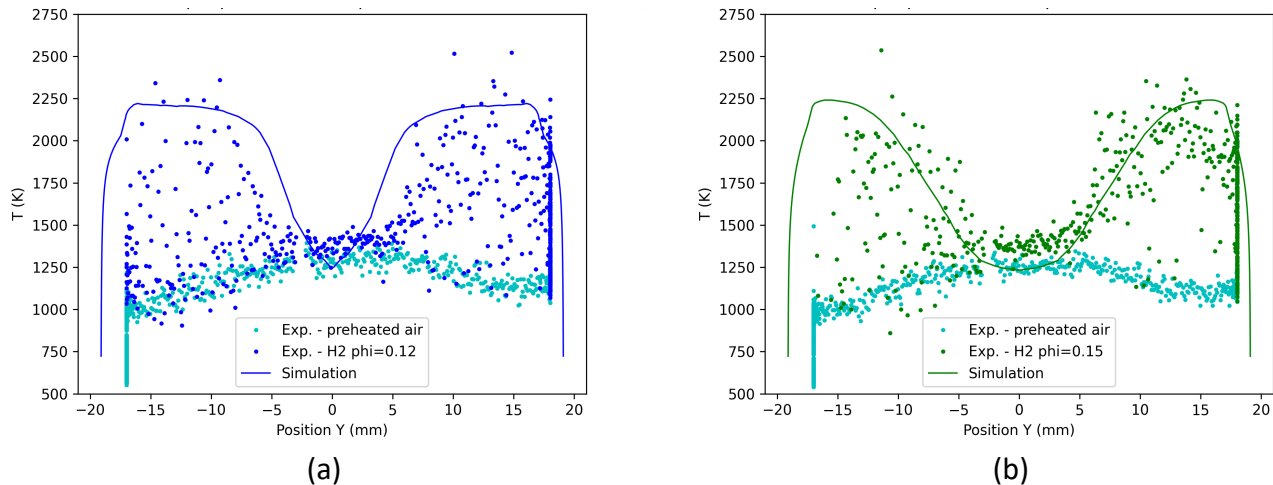


Figure. 6 Experimental temperature measurements (dots) during first scan in preheated air (cyan color) and during second scan (dark blue in a panel and green in b panel) versus height (y , vertical scan) at $x=160$ mm compared with numerical model (line) at (a) 0.12 and (b) 0.15 H_2 /air equivalence ratio injection.

Finally, closer to the injection, at 120 mm downstream the injector (vertical scan S1), high frequency temperature was characterized. The measured fluctuations prevented us to perform laser shot integration on the detector, as cold and hot spectra may accumulate, with the cold events being several orders of magnitude more intense than the hot events. However, single shot measurements were successfully performed at 1 kHz (Fig. 8 (a)) to reveal the very unsteady behavior of the flow. They allowed to retrieve reliable local temperature distributions revealing multimodal features typical of the intermittent mixing between hydrogen, air and burnt gases (Fig.9 (b)) while very smooth distribution patterns were measured in heated air prior to H_2 injection (Fig.9 (a)), providing a valuable input to refine the simulation of the incoming airflow structure. Two symmetric flame zones at the top and bottom of the combustion chamber were still identified in this plane, as observed in the other profile performed downstream. The last plane probed at 100 mm downstream the injector (vertical scan S0) showed no signature of combustion (Fig. 8 (b)) allowing to put a lower limit to the fluctuating flame front position.

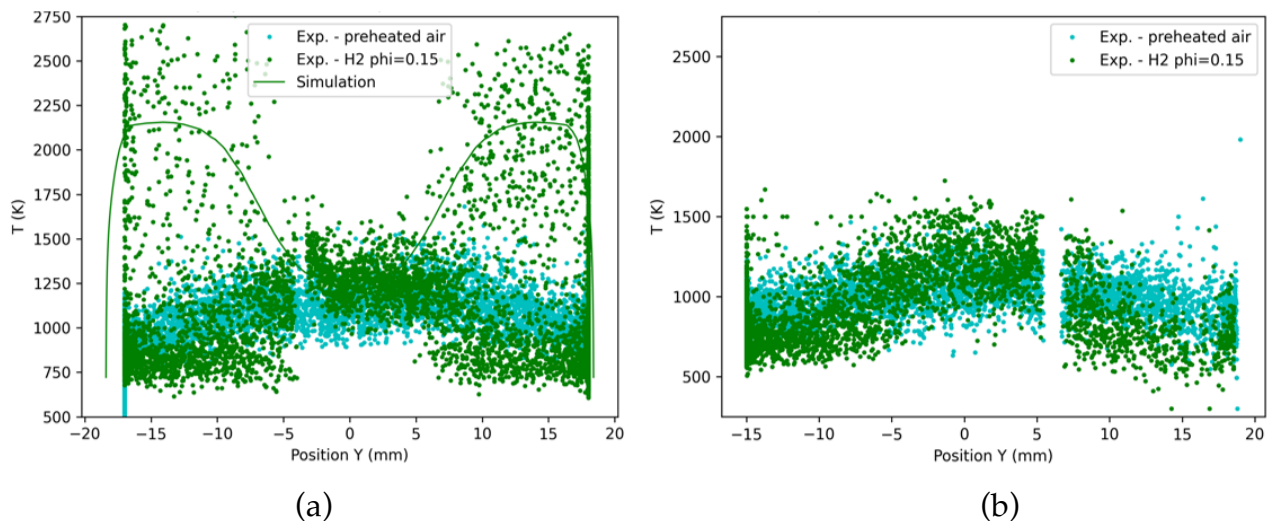


Figure 8 (a) 1 kHz single shot CARS measurements during vertical translation in a preheated air flow (cyan dots) and preheated air with H_2 /air injection (green dots) at (a) 120 mm and (b) 100 mm downstream the injectors. Continuous green line represents the results of the DDES simulation during hydrogen injection and combustion.

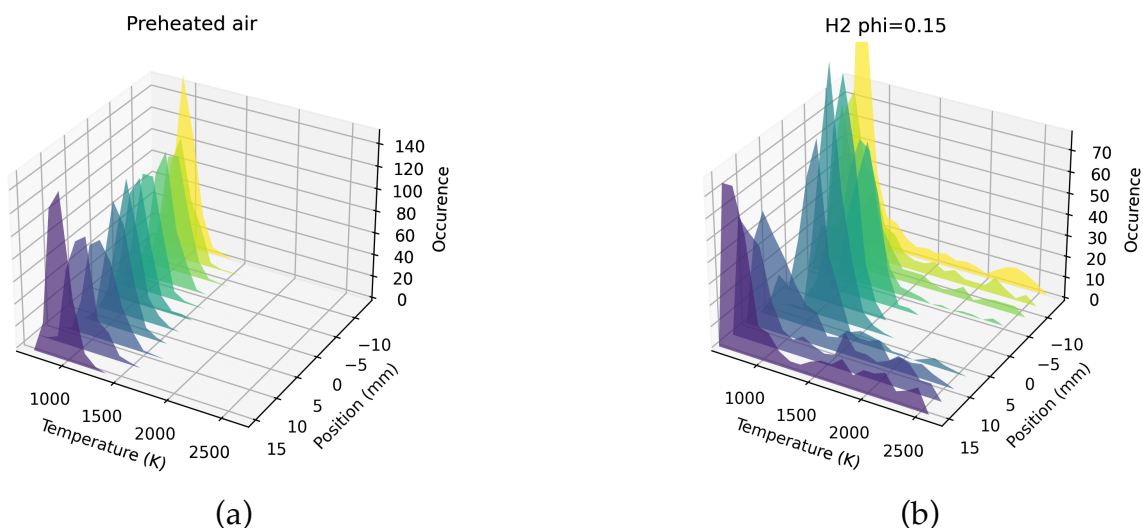


Figure 9 (a) Temperature distribution of preheated air flow and (b) preheated air with H_2 /air injection reconstructed at different vertical positions (from -12.5 mm to 17.5 mm) in the flow (vertical scan) during a single burst sequence. Vertical origin is taken in the middle of the chamber.

Two horizontal scans were performed at 1 kHz for $x < 140$ mm at $y = 12$ mm, and at 100 Hz for $x > 140$ mm at $y = -12$ mm (the flame structure is supposed symmetric between the top and the bottom parts). Between 40 and 140 mm, the hydrogen stream was monitored, injected colder than the preheated air, mixing with the flow and thermalizing. At positions higher than 140 mm, the temperature starts to rise as a signature of the combustion, reaching a plateau whose mean value agrees well with the simulations.

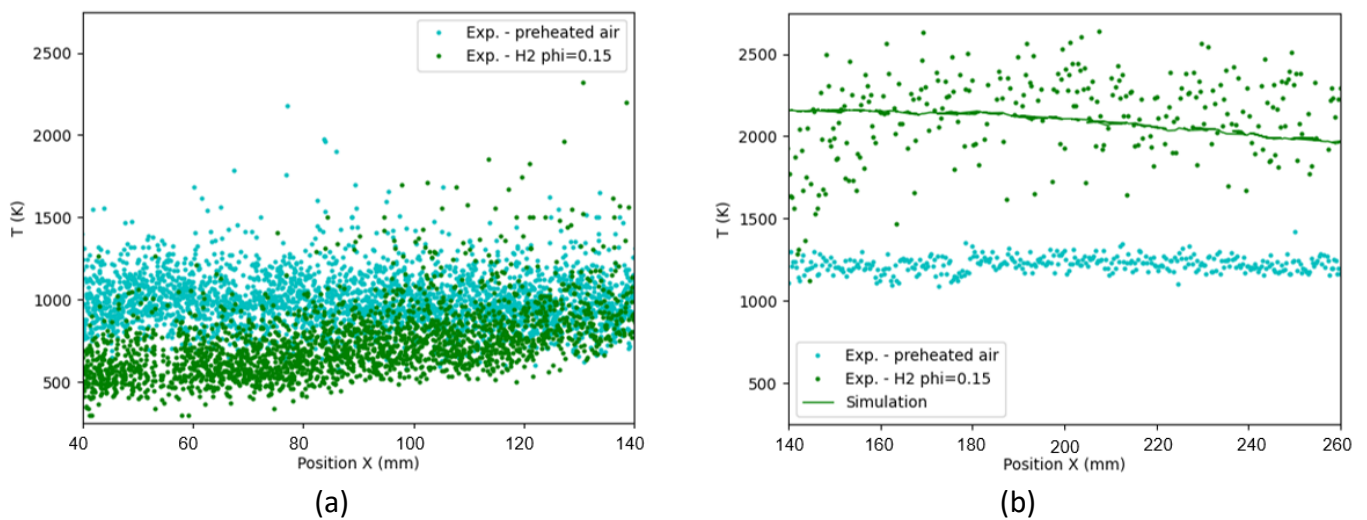


Figure. 10 Experimental temperature measurements (dots) versus position (x , horizontal scan) at (a) $y = -12$ mm in single shot between $x = 30$ and $x = 140$ mm and (b) $y = +12$ mm with 10 shot integration between $x = 120$ and $x = 260$ mm, compared with numerical model (line) at 0.15 H_2 /air equivalence ratio injection.

5. Conclusion

To conclude, we report kHz CARS thermometry measurements in a representative scramjet combustor. In-situ diagnostics was performed using a compact and mobile CARS laser bench. Experimental data were compared to numerical models developed at ONERA with good agreement. In highly fluctuating zones, single shot measurements provided a good insight into the turbulent behavior of the flow and provided reliable temperature distributions in various points, while in stable zones, precise temperature profiles could be obtained, revealing significant distortion with the simulation. These results are promising and provide a valuable dataset to significantly improve the models describing the LAPCAT-II supersonic flow structure.

References

- [1] Barros, J., Scherman, M., Lin, E., Fdida, N., Santagata, R., Attal-Tretout, B., & Bresson, A. (2020). 5 kHz single shot hybrid fs/ps-CARS thermometry in an atmospheric flame. *Optics Express*, 28(23), 34656-34664.
- [2] Druet, S. A., & Taran, J. P. E. (1981). CARS spectroscopy. *Progress in quantum Electronics*, 7(1), 1-72.
- [3] Eckbreth, A. C. (1978). BOXCARS: Crossed-beam phase-matched CARS generation in gases. *Applied Physics Letters*, 32(7), 421-423.

- [4] Nafa, M., Scherman, M., Bresson, A., Aubin, A., Godard, A., Attal-Tretout, B., & Joubert, P. (2016). Ro-vibrational spectroscopy in hybrid fs/ps-CARS for N₂ thermometry. *Aerospace Lab*, (12).
- [5] Patnaik, A. K., Adamovich, I., Gord, J. R., & Roy, S. (2017). Recent advances in ultrafast-laser-based spectroscopy and imaging for reacting plasmas and flames. *Plasma Sources Science and Technology*, 26(10), 103001.
- [6] Refloch, A., Courbet, B., Murrone, A., Villedieu, P., Laurent, C., Gilbank, P., ... & Vuillot, F. (2011). CEDRE software. *Aerospace Lab*, (2), p-1.
- [7] Richardson, D. R., Stauffer, H. U., Roy, S., & Gord, J. R. (2017). Comparison of chirped-pulse and hybrid femtosecond/picosecond coherent anti-Stokes Raman scattering for combustion thermometry. *Applied optics*, 56(11), E37-E49.
- [8] Roy, S., Gord, J. R., & Patnaik, A. K. (2010). Recent advances in coherent anti-Stokes Raman scattering spectroscopy: Fundamental developments and applications in reacting flows. *Progress in Energy and Combustion Science*, 36(2), 280-306.
- [9] Santagata, R., Scherman, M., Toubex, M., Nafa, M., Tretout, B., & Bresson, A. (2019). Ultrafast background-free ro-vibrational fs/ps-CARS thermometry using an Yb: YAG crystal-fiber amplified probe. *Optics Express*, 27(23), 32924-32937.
- [10] Scherman, M., Barros, J., Santagata, R., Lin, E., Nicolas, P., Faleni, J. P., ... & Bresson, A. (2021). 1-kHz hybrid femtosecond/picosecond coherent anti-Stokes Raman scattering thermometry of turbulent combustion in a representative aeronautical test rig. *Journal of Raman Spectroscopy*, 52(9), 1643-1650.