1-kHz hybrid femtosecond/picosecond coherent anti-Stokes Raman scattering thermometry of turbulent combustion in a representative aeronautical test rig.

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Abstract

The study of complex reactive flows met in aeronautical engines is an experimental challenge that requires the development of non-invasive and precise measurement techniques. Coherent anti-Stokes Raman scattering (CARS) is a standard spectroscopic technique used for temperature measurements, which provides unmatched reliability and accuracy at high repetition rate thanks to its recent adaptation to femtosecond temporal regime. This paper reports the first demonstration of hybrid fs/ps-CARS thermometry in a representative aeronautical combustor (ONERA MICADO test bench, Reynolds number $\approx 10^5$). Single shot N₂ CARS spectra have been recorded at 1 kHz, allowing temperature follow up, statistical and frequency (0.1-500 Hz) analysis of CH₄/air flame at 0.34 MPa total pressure. The achieved results demonstrate the ability of the technique to be applied in representative engines conditions and its maturity for semi-industrial applications.

Keywords: Raman, spectroscopy, thermometry, CARS, combustion

1. INTRODUCTION

Flow field measurement of state parameters in representative conditions is a challenge to overcome in aeronautics test facilities. This allows to understand the physical phenomena that take place in severe combustion environments, feeding databases to be compared with high fidelity simulations, in order to increase the trust level in models and to improve prediction. Among others, temperature is a prime parameter to access, as it governs the chemical reactions kinetics. Coherent anti-Stokes Raman scattering (CARS) spectroscopy ^[1,2] is conventionally used for temperature measurements in harsh environments^[3] (high temperature, highly luminous, non-equilibrium, high pressure, multi-phasic) since it provides strong signal level, good accuracy and precision, as well as temporal resolution in single shot measurement.

CARS is a nonlinear 4-wave mixing interaction. It involves two pulses, pump (ω_p) and Stokes (ω_s), for the two-photon excitation of the ro-vibrational coherences (Ω); a third pulse, the probe (ω_{pr}), interrogates these latter, and a fourth one, the anti-Stokes, generated satisfying energy conservation ($\omega_{AS}=\omega_{pr}+\Omega$) and phase matching rules, is blue shifted. The spectral content of the

CARS signal provides information on the thermodynamic properties of the molecular medium such as temperature, pressure and relative concentrations of major species.

Recent advances in CARS diagnostics were mainly led by the use of ultrafast femtosecond laser sources through the development of two major techniques, chirped probe pulse CARS^[4,5] (CPP-CARS) and hybrid fs/ps-CARS^[6,7]. While great improvements of the diagnostics have been recently achieved using hybrid fs/ps-CARS in laboratory conditions (kHz rate thermometry in point^[8] or line^[9] measurements, 2D-CARS^[10,11], ultra-broadband spectroscopy^[12]), only few applications in representative aeronautical engines conditions were demonstrated. The technique was indeed successfully used to probe heated and pressurized cells^[13,14], steady state combustion^[15] as well as unsteady flames^[16], high-pressure canonical flames^[17], compressible^[18] and hypersonic flows^[19], metalized propellants^[20], plasmas^[21] [22]. However, up to now, only CPP-CARS technique does demonstrate high-speed (kHz) measurements in quasi-industrial aeronautical combustor^[23-25].

In this paper, the first results of a measurement campaign carried out in a representative aeronautical combustor, the ONERA MICADO test facility^[26], using hybrid fs/ps-CARS thermometry of N₂ are presented. Turbulent combustion of CH₄/air is probed at 1 kHz repetition rate at several spatial locations to investigate the flame structure.

2. MATERIAL AND METHODS

The fs/ps-CARS thermometry technique has been evaluated on a highly turbulent CH₄/air flame at moderate pressure produced in the MICADO test rig. This facility, recently built at ONERA, has been developed to investigate combustion with advanced diagnostics in a single-sector combustor and test conditions that may cover the range of operation of a medium-haul aircraft engine (i.e. from idle to take-off)^[26]. A scheme of the combustor is presented in Fig. 1(a). Large optical accesses (88×89 mm²) enable optical diagnostics, as shown in Fig. 1(b).

Delivery tests demonstrated the ability of the facility to feed the combustor with up to 3 kg·s⁻¹ of air at 800 K and 2.8 MPa while combustion tests have so far been achieved between 0.2 and 1.2 MPa. As in real jet engines combustors, the fuel can be pilot (i.e. non-premixed) and/or main (i.e. premixed) injected to find the best compromise between stability and emission levels of greenhouse gas or pollutants species. Moreover, the MICADO injector can be fed either with liquid (kerosene Jet-A1) or gaseous fuels (methane or hydrogen). Air enters the 100×100 mm² dome of the combustor through an axial single-swirler (swirl number SN=1). In the frame of this paper, the presented experimental data deal with combustion of pilot injected CH₄ in preheated air ($T=563$ K) at moderate pressure $P=0.34$ MPa, air mass flow rate $\dot{m}_{\text{air}}=0.343$ kg·s⁻¹, and equivalence ratio $\Phi=0.59$ leading to an adiabatic temperature around $T_{ad}=1850$ K and a Reynolds number $Re\approx 10^5$.

The measurement setup is depicted in Fig. 2. The mobile and compact (<1 m²) optical table contains the devices to generate the 3 CARS beams, i.e. pump, Stokes and probe, according to the configuration previously described^[27]. It is based on a single Yb:KGW laser (LightConversion) which emits a train of 1 mJ pulses (175 fs, 1030 nm) at a repetition rate

between 1 and 5 kHz^[28]. During the campaign, the latter was limited to 1 kHz. It pumps an optical parametric amplifier (OPA, LightConversion) in which idler radiation's second harmonic produces the 15 μ J Stokes pulse (150 fs, 583 nm). A 100 μ J leakage of the frequency-doubled fundamental beam (335 fs, 515 nm) is used as the pump pulse, and a residue from fundamental beam is filtered, amplified and doubled to generate a 100 μ J narrowband probe pulse (58 ps, 515 nm). The beams are recombined using a dichroic filter and arranged in a folded BOXCARS geometry using two achromatic lenses of 150 mm focal length (L1 and L2 in Fig. 2). After propagation through a 50 mm thick window (fused silica), the beams are crossed at the focal point with an angle of 3.8° and the anti-Stokes is generated in a narrow measurement volume (cylindrical-like shape, approximatively 0.1 mm in diameter and 1.5 mm long). In the temporal pulse sequence used here, the probe is not delayed from the pump/Stokes excitation in order to maximize the CARS signal and minimize pressure influence. Due to group velocity dispersion in the silica material, the femtosecond pulses are frequency chirped which slightly narrows the excitation spectral window from ~ 150 cm^{-1} to ~ 90 cm^{-1} , still wide enough to probe the three first ro-vibrational bands needed for precise temperature measurement at flame temperature.

The anti-Stokes beam is isolated through spatial and spectral filtering, and analyzed through a 750 mm spectrometer (Acton, Teledyne Princeton Instruments) equipped with an electron multiplying charge-coupled device (EMCCD, ProEM+, Teledyne Princeton Instruments). During rig operation, polarization elements were removed from the detection path to minimize the effects of potential degradation of the polarization state by the heated and pressurized windows. In the following, the y axis is vertical, and the z axis is horizontal and orthogonal to the flow direction. The origin position $(x;y;z)=(0;0;0)$ is located at the output of the pilot fuel injection nozzle. For the sake of spatial investigation of the flame structure, L1 and L2 lenses are mounted on micrometer precision motorized stages (Newport Microcontrole, M-MTM series, stepper motor) inserted before and after the chamber and placed on two distinct platforms translated in the flow direction parallel to the x axis (Fig. 2). The robustness and reproducibility of the displacement was checked by translating successively excitation and collection optics and monitoring signal amplitude. No realignment of the CARS beams was necessary during the scan except slight spectrometer injection adjustment after 20 mm displacement.

3. INVESTIGATION OF MICADO CH₄/AIR FLAME

Single shot N₂ CARS spectra were acquired at 1 kHz repetition rate in MICADO. Typical experimental spectra are presented in Fig. 3 (blue curve). Time duration of each dataset is 10 s, providing 10000 raw spectra analyzed with a fast Python3 routine elaborated for that purpose. Prior to fitting routine, frames exhibiting too low signal-to-noise ratio, or a background being either too intense compared to signal amplitude or highly distorted were removed from the final dataset. The number of fitted data was always higher than 93% of the total amount, as given in Table 1, providing good relevancy of measured temperature for statistical analysis. Fits are performed using a procedure similar to that described in our previous works^[29,28]. Collisional effects were modeled using a Modified Exponential Gap (MEG) law^[30,31] to calculate the linewidths of the Raman lines assuming only N₂-N₂ interactions as a first approximation at this

pressure with small probe delay. Pressure was measured in real time and used as a known parameter in the simulation. Pump/Stokes excitation profile is taken into account by recording pure nonresonant CARS spectra in the chamber filled with argon prior to the combustion test and after it. Best fit (orange curve in Fig. 3(a)) exhibits good agreement with experimental spectrum (blue line), leading to a low residual contribution (green line). The fit is performed using five optimization parameters, namely: temperature, signal amplitude, spectral displacement (horizontal translation on the EMCCD), nonresonant contribution, and a saturation parameter labeled A_{sat} .

While saturated signals are usually discarded from post-processing, we chose to add the variable A_{sat} to the fit to truncate the signal above this amplitude value in order to simulate the EMCCD saturation process and to allow these spectra to be fitted properly. This allows us to increase by up to 23% the number of useful experimental data taken into account into a single dataset, as shown in Table 1. A typical saturated spectrum, acquired during a cold gas event, is illustrated in Fig. 3(b) (blue line). The simulated spectrum (orange line) exhibits good agreement with the unsaturated part of the experimental one, even if abruptness of the transition between the saturated and unsaturated zones may induce, at the interface, some visible sharp features on residual data (green line). As expected, the saturation parameter A_{sat} induces a plateau profile in the corresponding saturation zone of the data. This parameter thus specifies a tunable spectral zone that is excluded from the CARS simulation, and replaced by a constant unitary value, while the unsaturated zone keeps on providing relevant temperature information thanks to its characteristic and meaningful spectral shape.

The increase of saturated frames count in the flame is due to the highly turbulent structure of the flame. Indeed, hot and cold gases coming respectively from heated air and burned gases alternate at the measurement volume and induce very high signal amplitude variations on the detector. This is illustrated in Fig. 4(a) (blue dots), which shows the influence of temperature, in the range 400-2400 K, on the CARS signal detected by the EMCCD. The data comes from two datasets recorded at the same location with identical combustor conditions, but with different EMCCD gains, namely $G=30$ and $G=100$. CARS signal amplitude (blue dots), taken at the maximum of the CARS spectrum, and noise (green dots), calculated as the standard deviation of the signal in the $2377\text{-}2430\text{ cm}^{-1}$ spectral region, are plotted in logarithmic scale. The noise level appears to be independent from temperature but is linked with EMCCD gain (~ 50 counts for $G=30$, and ~ 130 counts for $G=100$). On the other hand, the CARS amplitude exhibits a variation of almost two orders of magnitude, and signal saturates when its amplitude increases beyond $65536 (=2^{16})$ due to the limited dynamic range of the 16 bits detector. We would remind that, because of the square dependence of the CARS signal to the number density of N_2 emitters, hot gases produce a low intensity CARS signal, while cold gases generate a very intense one. Moreover, at high temperature ($T > 2000\text{ K}$), the N_2 ro-vibrational profile is spreading over more than 100 cm^{-1} , including three vibrational branches, while it is restricted to a narrow spectral range of a few wavenumbers at lower temperature ($T < 1000\text{ K}$), as illustrated in Fig. 3(a) and (b). Indeed, it increases even more the gap between cold and hot signals intensities.

This behavior limits the measurement dynamics and is strongly influenced by the EMCCD gain value as shown in the two plots of Fig. 4(a). For $G=30$, the signal-to-noise ratio (SNR) is varying from 20 to 160 when the temperature decreases from 2200 K to 1000 K, and starts to be saturated below ~ 800 K. For $G=100$, the SNR is varying from 24 to 210 in the same temperature range, and starts saturating below ~ 1000 K. In order to maximize the temperature coverage as well as the SNR of the measurement, previous studies proposed to delay the probe pulse to an optimized value^[32-34], or use a dual-channel detection system^[35]. In our case, we work at zero delay and make a compromise on the gain G of the detector in order to enhance low intensity signals such as to retrieve spectra coming from hot gases with good enough SNR. Then, we retrieved the low temperature side of the dynamic range by partly allowing saturated data to be effectively processed. The gain G was modified during the campaign (Table 1) depending on the mean signal intensity, i.e. average local temperature.

The effect on the probability density function (PDF) reconstruction is illustrated in Fig. 4(b), which shows the histograms of measured temperature drawn from the two previously described datasets (in green for $G=30$ and in blue for $G=100$). In the two cases, the PDF profile depends on the rejection (continuous line) or the admission (dashed line) of the saturated frames during the data processing. As expected, the rejection of the saturated frames is observed to bias the temperature distribution towards the high values, by underestimating the low temperature side of the PDF ($\langle T \rangle = 987$ K for $G=30$ and $\langle T \rangle = 1093$ K for $G=100$). This effect is even more pronounced at higher gain, when the number of saturated frames increases (13% of all frames for $G=30$ compared to 35% for $G=100$) making the retrieved mean temperature value greatly influenced by EMCCD gain (gap of 106 K between $G=30$ and $G=100$). However, with due account of saturated frames into the treatment, a very similar pattern is observed for the PDF computed at the two different gain values ($\langle T \rangle = 935$ K for $G=30$ and $\langle T \rangle = 922$ K for $G=100$). The cold side lobe of the PDF is indeed well reconstructed and a mean temperature difference which is divided by 8 (gap of 13 K between $G=30$ and $G=100$). This observation validates this fitting process and the relevancy of analyzing the full dataset labeled “Fitted frames” in Table 1. This study demonstrates that all frames have to be taken into account to properly retrieve the PDF. Otherwise, sorting may distort the temperature distribution especially in the low temperature side, and distortion is even more pronounced at higher gain values of the EMCCD detector.

Fig. 5 shows the temperature follow-up measured during 10 s acquisition sequences (bottom curves) at $(x;y;z)=(40;15;0)$ mm inside the MICADO chamber filled with pre-heated air ($T=503$ K measured with a thermocouple located upstream from the combustor), and during typical combustion run. In order to analyze the flame structure, the spatial position was scanned in the x direction from upstream ($x=40$ mm) to downstream ($x=65$ mm) during the combustion reaction at constant height $y=15$ mm. The average value and standard deviation of the temperature measurements performed at various locations in the combustor are summed up in Table 1. While a constant temperature is observed when the flame is off, the dispersion of the measurement strongly increases during combustion, as a result of the induced turbulences. Heated air temperature is measured with good accuracy (3%). A zoom over 300 ms is given in

Fig. 5 (upper curves). It highlights that the technique cannot resolve coherent structures due to the too low repetition rate of the measurement (1 kHz) as regards the turbulence intrinsic temporal dynamics. The translation of the measurement volume in the flame zone, from injector toward downstream is however interesting. It results in a significant increase of the mean temperature as well as in an evolution of the temperature distribution as described below.

Histograms are computed for each dataset and pictured in Fig. 6(a). A narrow temperature distribution is observed in pre-heated air, with corresponding 500K temperature, whereas the combustion clearly distorts the shape by broadening the distribution between $x=40$ mm and $x=50$ mm as a signature of a recirculation zone. Moreover, a second lobe appears between $x=55$ mm and $x=65$ mm on the high temperature side of the distribution, outlining the burning zone. It is centered on the adiabatic temperature of the flame in these conditions $T_{ad}(\Phi=0.59)=1850$ K (thick dotted line). The lobe spreads up to the theoretical maximum temperature of a premixed flame $T_{ad}(\Phi=1)=2350$ K (thick dashed line). Indeed, the turbulent flow produces a broad distribution of mixing conditions and stoichiometric conditions can be met locally in the flame. However, few events exhibit a temperature slightly higher (up to 2500 K) in the tail of the lobe, which is attributed to poor fitting routine convergence when the signal to noise ratio is too low, as could be met for some events at high temperature in these fast and turbulent conditions. This bi-modal distribution is characteristic of the alternation of hot and cold gases at the measurement volume as a result of the turbulent mixing layer of burned and fresh gases that induces a fast displacement of the flame front zone.

The fast Fourier transform (FFT) is calculated for the previously considered data and illustrated in Fig. 6(b) with a 50 points (standard deviation) Gaussian smoothing. In heated air, we observe few distinct signatures, the two most pronounced being at 60 Hz and 190 Hz. Their origin is not clearly identified at the moment although probably linked to acoustic waves propagation in the 4-m long air inlet pipe or to the precession frequency of the vortex core. When the flame is on, the 190 Hz peak is the only one observed, although slightly shifted to 200 Hz position, and becoming weaker when the measurement volume is moved further away from the injector.

4. CONCLUSIONS AND PERSPECTIVES

We performed CARS thermometry at 1 kHz repetition rate in a representative aeronautical combustor. Turbulent combustion of CH_4/air was probed in various locations in order to investigate the flame structure in canonical conditions and validate the performances of the diagnostics. High temperature variations were retrieved, thus saturated frames were included in the post-processing routine in order to increase the percentage of fitted frames in each dataset. Characteristic frequencies of the flow were measured and a bi-modal structure was revealed by temperature histograms, as a signature of turbulent combustion.

The accuracy of hybrid CARS technique was thus here combined to a precise temporal sampling process and to a pertinent theoretical treatment of the spectral profiles leading to temperature statistics almost able to probe turbulence, with some improvements, in the near future. To go further, another campaign with kerosene/air injection was also performed, and

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data are under study to compare the flame structure and temporal dynamic depending on the fuel injection.

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Label	EMCCD gain	Fitted frames	% of which are saturated	<T> (K)	Standard deviation (K)
Heated air	1	9998	0	487	54
40 mm	3	9981	4	756	280
45 mm	3	9981	6	797	282
50 mm	30	9951	12	858	346
55 mm	30	9859	13	935	436
60 mm	100	9708	23	1061	521
65 mm	100	9357	12	1167	574

Table 1. Main acquisition and post-processing parameters for the data presented in this study. The values in mm reported in the first column refer to measurements locations along the x axis.

Fig. 1. (a) Schematic of the MICADO facility. (b) Side view of the MICADO combustor during operation.

73x30mm (300 x 300 DPI)

Fig. 2. Experimental setup. Various positions (coloured dots in the side view of the combustor window) are probed with CARS in the x direction parallel to the flow by translating the optics upstream and downstream from the combustor using motorized translation stages. OPA, optical parametric amplifier; MOPA, master oscillator power amplifier; SHG, second-harmonic generation; IF, interferential filter; EMCCD, electron-multiplying charge coupled device; MTS, motorized translation stage; L1, L2, BOXCARS lenses; S, Swirl.

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Fig. 3. Typical CARS spectra (blue), best fit of simulated spectra (orange) and residual (green) in the case of data recorded in (a) hot gas and (b) cold gas with sometimes saturation of the EMCCD detector.

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Fig. 4. (a) CARS signal (blue dots) and noise (green dots) amplitudes (in logarithmic scale) of each spectrum of a 10 s dataset versus temperature retrieved from the fit. Two datasets are measured successively at the same measurement volume and the same combustor operating conditions, with different EMCCD gain values of 30 (left) and 100 (right). (b) Histograms of temperature retrieved from the two measured datasets are plotted (in green for G=30 and in blue for G=100) considering unsaturated frames only in continuous lines ($\langle T \rangle = 987$ K, std=443 K for G=30; and $\langle T \rangle = 1093$ K, std=444 K for G=100) or all frames in dotted lines ($\langle T \rangle = 935$ K, std=436 K for G=30; and $\langle T \rangle = 922$ K, std=448 K for G=100).

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Fig. 5. Temperature follow-up performed at 1 kHz in the MICADO chamber over a 10 s temporal window (bottom curves) with a zoom over a 300 ms temporal window (top curves); (a) in heated air at $x=40$ mm and (b) during CH_4/air combustion at $x=65$ mm.

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Fig. 6. (a) Temperature histograms and (b) Fourier Transform of temperature measurements as a function of flow condition and spatial location of the probe volume. Two lines are added on the histograms to outline the two adiabatic temperatures $T_{ad}(\Phi=0.59)=1850 \text{ K}$ (green dotted line) of lean flow conditions, and $T_{ad}(\Phi=1)=2350 \text{ K}$ (red dashed line) of stoichiometric mixture.

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