

Spontaneous Raman thermometry mapping of an overexpanded supersonic jet

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ABSTRACT

This work reports in-situ non-invasive temperature measurements performed by spontaneous Raman scattering thermometry in a large-scale round free-stream stationary supersonic air jet produced by the ADIJE facility (DIphasic Analysis of Jets) at ONERA.

Since maintaining adapted jet during the whole flight of a supersonic vehicle is generally impossible, mainly due to the ambient pressure that varies greatly with the altitude, increasing knowledge on non-adapted jet is still valuable today. Non-adapted supersonic flows generate shock structures associated with intense thermodynamic gradients. Recent experimental studies show that shock/boundary-layer interactions can produce local temperature increase exceeding 50 K and heat flux distributions that are strongly correlated with the dynamics of the shock structures (Lin et al., 2025). As these phenomena are highly localized, their characterization requires advanced optical diagnostics capable of measuring temperature within shock regions with good precision and spatial resolution.

Spontaneous Raman scattering thermometry is employed to investigate the temperature distribution within the jet, which exhibits a cellular shock structure. The medium is excited using a continuous monochromatic laser radiation at 532 nm emitted from a high-power fiber laser (10 W) focused using a 150 mm focal length lens. The backward spontaneous Raman scattering is collected and analyzed in a 300-mm focal spectrometer. The well-resolved rotational structure of N₂ and O₂ follows a Boltzmann distribution that is fitted to estimate the internal temperature at the measurement volume.

Hyperspectral data are acquired by scanning the measurement volume across the flow in several planes of interest. Precise temperature maps are retrieved with an unprecedented mapping in terms of both spatial resolution and measurement coverage, exhibiting a complex shock structure characteristic of overexpanded supersonic jets, and showing a very good agreement with the temperature field simulated by Large Eddy Simulation (LES). The achieved results outline the performance of spontaneous Raman scattering thermometry to provide in-situ quantitative diagnostics in realistic supersonic jets with the aim of build highly valuable experimental databases as a support for model validation.

1. Introduction

Convergent-divergent nozzles are widely used to allow vehicles, such as rocket, to reach supersonic velocity. However, the thrust balance and the structure of a supersonic jet at its exhaust is linked to

the ratio between the static pressure at the nozzle exit and the ambient pressure (Simmons, 2000). Characterizing non-adapted jets, in which complex spatial structures arise from shock interactions and strong compressibility effects, is crucial for nozzle optimization, jet noise reduction (André et al., 2013) or the assessment of jet aerothermochemistry, plume signature and loads on the aft body (Langenais et al., 2023). Therefore, establishing a reliable experimental database via non-intrusive diagnostics is necessary to optimize and validate the numerical models. Moreover, given the highly localized feature of shock cells, their characterization necessitates advanced quantitative diagnostics capable of resolving temperature variations within the shock regions, thus allowing to assess the predictive capabilities of computational fluid dynamics (CFD) simulations (Brès et al., 2017, Langenais et al., 2021).

In that context, a suitable diagnostic is spontaneous Raman scattering (RS), a well-established spectroscopic technique (Eckbreth, 1996; Long, 1977; Weber, 1979) proven for gas-phase thermometry (Dibble, 1987) as it allows temperature and concentration measurements of major diatomic species. It uses a single excitation laser and a simple optical arrangement, making it particularly reliable and robust in harsh environments subject to vibrations and acoustic noise. Spontaneous RS results from inelastic interaction between light and matter as incoming radiation is scattered by the molecules with a frequency shift characteristic of the vibrational and rotational molecular energy. The temperature can be estimated from the amplitude pattern of the Raman lines reflecting the Boltzmann distribution of population over the ro-vibrational manifold. In particular, RS is well suited to probe stationary media because it requires long acquisition times (seconds to minutes) due to weakness of the Raman cross section, although single shot capability has also been demonstrated using high energy pulsed lasers (~500 mJ per pulse) to address reacting flows (Locke et al., 2018; Gu et al., 1997).

A particular case of RS is the study of the low-wavenumbers (0-500 cm^{-1}) rotational lines, well adapted to temperature measurement up to 1000 K. Rotational spontaneous RS was used to measure temperature for various applications among which a high-velocity turbulent jet (Locke et al., 2018), a gas turbine model combustor at elevated pressure (Thariyan et al., 2010), a confined swirling natural gas/air flame (Keck et al., 2002), in high-pressure fuel-rich H_2 -air flames (Kojima and Nguyen, 2004) and in a Jet A-fueled aircraft combustor. The accuracy of rotational RS technique was shown to be very good at ambient temperature: Drake et al. (Drake et al., 1978) have mentioned an accuracy of 2 K at about 300 K (i.e. ~0.7 %) using signal accumulation over 45 s, while Locke et al. (Locke et al., 2018) have shown an accuracy of 6.5 K at 296 K (i.e. ~2.2%) in single shot.

At ONERA, the possibility to make use of rotational spontaneous RS to achieve temperature measurements was previously demonstrated in a transonic compressor (Berreby et al., 2001) using

a pulsed 532 nm laser system and achieving a 1 K absolute accuracy over 300–800 K using signal accumulation over 20 s. In a more recent work (Scherman et al., 2019), we demonstrated rotational spontaneous RS measurements in a turbomachine test rig using a pulsed 532 nm laser system and we successfully retrieved temperature maps across multiple planes over 350–500 K.

This work reports the use of rotational spontaneous RS for thermometry in a round free-stream supersonic heated air jet produced by the ADIJE facility at ONERA, equipped with a convergent-divergent de Laval nozzle and producing a flow reaching Mach 2.6 in order to simulate gas exiting the nozzle of a supersonic vehicle. The 2D-fields are reconstructed by concatenating successive 1D temperature profiles performed either radially (~60 mm long displacement) or axially (~250 mm long displacement) on the temperature range between 150 K and 600 K.

Raman thermometry has been previously used to investigate supersonic jets (Tejeda et al., 1996; Wernet et al., 2021; Wu et al., 2015), and probe the temperature field in the vicinity of a Mach disk produced by an overexpanded hot air jet. However, to the best of the authors' knowledge, the temperature maps presented in this work are unprecedented in both sampling density and spatial extent, allowing detailed and unambiguous reconstruction of the topology of multiples shock cells, with a state-of-the-art precision at ambient temperature of 0,9 K, i.e. ~0.3 % of mean value 291.7 K, using signal accumulation over 1 s.

2. Material and methods

Experiments were conducted on a round free-stream heated air jet exhausting from a convergent-divergent nozzle, with a throat diameter of 19.4 mm and an exit diameter of 40 mm. The operating conditions were an inlet pressure of $P_i=21$ bar, an inlet temperature of $T_i=670$ K and a mass flow rate of $m=0.95$ kg/s. The flow expands to atmospheric pressure, leading to an overexpanded supersonic jet. The corresponding ideally expanded Mach number is 2.6

The experimental setup is reported in Figure 1 (a). The laser source consists of a high power Ytterbium fiber laser that generate a continuous monochromatic laser radiation at 1064 nm that is frequency doubled to 532 nm thanks to a second-harmonic generation stage (Azurlight, 10 W). Because of the harsh conditions existing in the experiment room (~156 dB acoustic noise), the laser is positioned in an adjacent room and the beam is guided in free space over few meters to the test rig, and finally focused on the jet axis using a 150 mm focal length lens (Figure 1 (b)).

The backward spontaneous Raman scattering is collected using the excitation lens (2" diameter) for a robust optical design (Figure 1 (a)) facilitating the scan of the measurement volume. The Stokes spectrum is analysed using a 300-mm focal spectrometer (Isoplane SCT 320) equipped with an EMCCD camera (ProEM, Princeton Instrument). A dichroic razor-edge filter (<50 cm⁻¹ edge) efficiently rejects the excitation light and transmit the red-shifted Raman scattering.

The excitation and collection optics are mounted on two remotely controlled motorized translation stages (Newport) enabling wide spatial scanning of the measurement volume in two orthogonal directions along the x axis parallel to the jet direction (as illustrated in Figure 1 (a)) and in the transverse vertical direction y (translation stages not shown in the picture for simplicity). The investigated XY planes are mapped at constant position of the transverse horizontal axis z. Hyperspectral data acquired through scanning are used to build temperature maps in several planes of interest.

We localized precisely the measurement volume prior to measurements by detecting Raman signal cancellation in an argon flow exiting from a pipe having a radius $r=2$ mm set on a micrometric translation stage. A maximum of 90% of signal suppression was measured with this pipe, enabling us to estimate the probe length full width at half maximum to $l = r\sqrt{2\ln(2)} \sim 2.4$ mm in the laser propagation direction, i.e. in the horizontal direction orthogonal to the flow, considering a gaussian shape of the emitted signal. In the direction transverse to the laser direction, the laser spot is expected to be ~ 100 μm in diameter, however the true spatial resolution is rather limited by the scanning speed of the translation stages as the signal is continuously acquired during the scan and thus integrated between two acquisitions of the EMCCD camera separated by 1 second each. In both vertical and horizontal axis, the translation speed is set to 1 mm/s providing a resolution of 1 mm in the scanned direction.

The internal temperature (static temperature of the flow) is extracted from the rotational Raman signals by fitting simulated spectra (Locke et al., 2018) of a mixture of O₂ and N₂ molecular species which are major components of the heated air jet contributing to the Raman signal.

Pure rotational Raman spectrum is retrieved according to selection rules $\Delta v = 0$, and $\Delta J = +2$ for the S branch investigated, where v and J are the vibrational and rotational quantum numbers. Spectral lines are clearly identified using the following expression describing their position:

$$\Delta_{v_s} = (4B_0 - 6D_0) \left(J + \frac{3}{2} \right),$$

where $\Delta_{v_s}(J)$ is the Raman shift associated with the transition originating from the lower level J , and B_0 and D_0 are respectively inertial and centrifugal distortion constants of the molecule ($B_0=1.98957$ cm^{-1} and $D_0=5.76 \cdot 10^{-6}$ cm^{-1} for N₂).

3. Results and discussions

Typical rotational Raman spectra acquired with 1 s integration time are reported in Figure 2 (a) and (b) for respective low and high temperature regions of the jet. A python routine is then used to retrieve the temperature (Scherman et al., 2019).

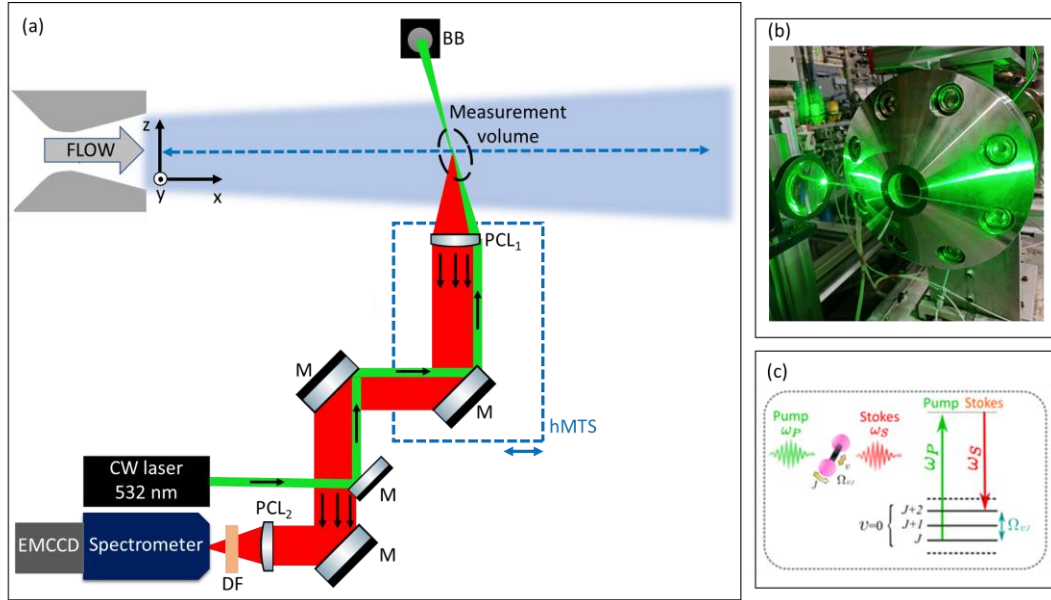


Figure. 1 (a) Simplified top view experimental setup, (b) picture of the laser beam focused on the jet axis close to the ADIJE nozzle, and (c) energy transfer process in rotational Raman process. For the sake of simplicity, the scheme shows the horizontal scan only. M: optical mirror; PCL: plano-convex lens; DF: dichroic filter; BB: beam blocker; hMTS: motorized translational stage used for horizontal scan.

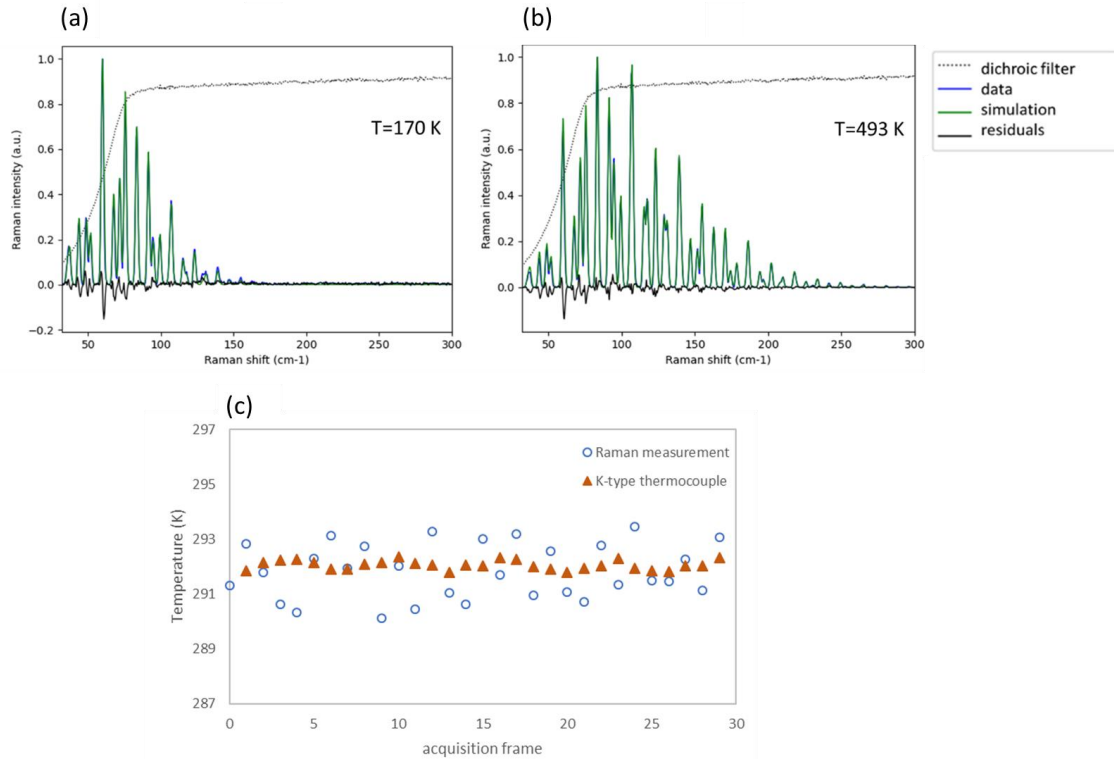


Figure. 2 (a) and (b) Experimental Raman spectra (blue), best fit (green), and residual (black), of data acquired in (a) low and (b) high temperature region of the jet. Transmission of the dichroic filter is also given in dotted line. (c) Temperature measurement performed at ambient temperature using Raman spectra ($\langle T_{\text{Raman}} \rangle = 291.7 \text{ K} \pm 0.9 \text{ K}$) and a reference K type thermocouple ($T_{\text{TTC}} = 292.0 \text{ K}$) having an accuracy of $\sim 1.5 \text{ K}$.

The experimental spectra (blue line) exhibit a well-resolved rotational structure of N₂ and O₂ with a strong dependence with temperature as a signature of the Boltzmann distribution. Simulated spectra (green line) are fitted to estimate the internal temperature with good agreement (residual indicated in black). A set of 30 spectra taken in ambient air allows to estimate the temperature with good agreement compared with local thermocouple, as illustrated in Figure 2 (c). By calculating the standard deviation over the 30 measurements, a precision of $\sigma_T = 0.9 \text{ K}$ is estimated at ambient temperature and pressure, i.e. $\sim 0.3 \%$ of mean value $\langle T_{Raman} \rangle = 291.7 \text{ K}$, using signal accumulation over 1 s.

Figure 3 (a) and Figure 4 (a) reports two experimental temperature maps acquired in the XY plane intersecting z axis at respectively $z=0 \text{ mm}$ and $z=3 \text{ mm}$. The achieved maps, obtained during two different experiment sessions of roughly one hour of stabilized conditions, exhibits a complex shock structure characteristic of overexpanded supersonic jets, showing good agreement with the temperature field simulated by LES (Jalain et al., 2026) reported in Figure 3 (b) and Figure 4 (b)). Figure 3 (a) is obtained by concatenating 11 horizontal scans (with a vertical spacing between each profile of 2.5 to 5 mm) of 270 measurement points (1 mm horizontal sampling indicating by the superimposed dots). In addition to the maps, horizontal profiles are reported in Figure 3 (c) and Figure 3 (d), at $y=0$ (i.e. intersecting the Mach disk inside the first shock cell) and at $y=5 \text{ mm}$ (i.e. just above the Mach disk) respectively. They clearly illustrate the ability of the diagnostics to localise the positions of the three shock cells, to determine theirs size and shape, and to resolve high spatial gradients at the vicinity of the shocks. In Figure 3 (c), we can observe that the positions of the two first shock cells are well predicted by the simulation although the temperature rise appear to be underestimated by the simulation. Figure 3 (d) shows that downstream the shock there is a great accordance between experiment and simulation even if the simulated data still seem to slightly overestimate the temperature of the flow.

Near the shock wave, care should indeed be taken in interpreting temperature data, as the measured rotational temperature may differ from the translational temperature due to local non-equilibrium (Wu et al., 2015). PIV (Particle Image Velocimetry) and FLEET (Femtosecond Laser Electronic Excitation Tagging) velocity measurements performed on the same jet revealed a significant velocity drop in these regions confirming the shock positions (Jalain et al., 2026; Bernardot et al., 2026). However, the axial velocities measured experimentally by both techniques never decrease below 200 m/s while negative velocities are determined by the simulation. This supports the argument that higher simulated temperatures can be associated with a compression effect through the Mach disk that seems spuriously amplified by the LES model. An additional source of underestimation of jet temperature is that the experimental temperature field is

intrinsically averaged over the measurement volume, while the simulated one doesn't take this effect into account.

Figure 4 (a) focuses on the structure of the first shock cell by concatenating 34 vertical scans (with a horizontal spacing between each profile of 2.5 to 5 mm) of 60 measurement points each (1 mm vertical sampling indicated by the superimposed dots) and performed to probe approximately $y = -30$ mm to $y = 30$ mm. The resulting map shows good agreement with the simulated temperature field simulated illustrated in Figure 4 (b). Figure 4 (c), (d), and (e) present three vertical profiles extracted in the vicinity of the nozzle outlet ($x=5$ mm), upstream of the Mach disk ($x=42.5$ mm), and downstream inside the subsonic pocket ($x=50$ mm). The experimental and simulated data match again very well in amplitude and position, underlying the ability of the diagnostics to resolve the complex structures of the flow and the capacity of the simulation to reproduce it in the vicinity of the first shock cell. In particular it is remarkable to observe that the boundary layer, that in the simulation is expected to enclose the shock structure, is well observed also in the vicinity of the nozzle outlet where it is very thin, even if it is poorly resolved in the experimental profile acquired at $x=5$ mm (Figure 4 (c)). This is attributed to spatial averaging during the integration time (~ 1 mm) leading to underestimation of the peak temperature, but also to the fact that the LES model used in this work does not consider heat losses that occur as the flow approaches the wall, overestimating the boundary layer temperature.

Upstream the shock, at $x=42.5$ mm (Figure 4 (d)), the shape and amplitude of the experimental temperature profile are in very good agreement, even in regions exhibiting high temperature gradients. Downstream of the shock, i.e. in the subsonic pocket, while the size of the pocket is well reproduced, the maximum temperature value appears significantly overestimated by the simulation (Figure 4 (e)), as discussed previously. The fact that the LES temperature is generally higher can be observed also for the temperature of the boundary layer (Figure 4 (c)). Finally, for the three vertical profiled here reported we can observe a slight gap of temperature (~ 15 K) between the upper ($y=30$ mm) and lower ($y=-30$ mm) positions on the experimental data that is not reproduced by the simulation, probably indicating that jet, or secondary flows of ambient air induced by the jet, are probably slightly non-axisymmetric.

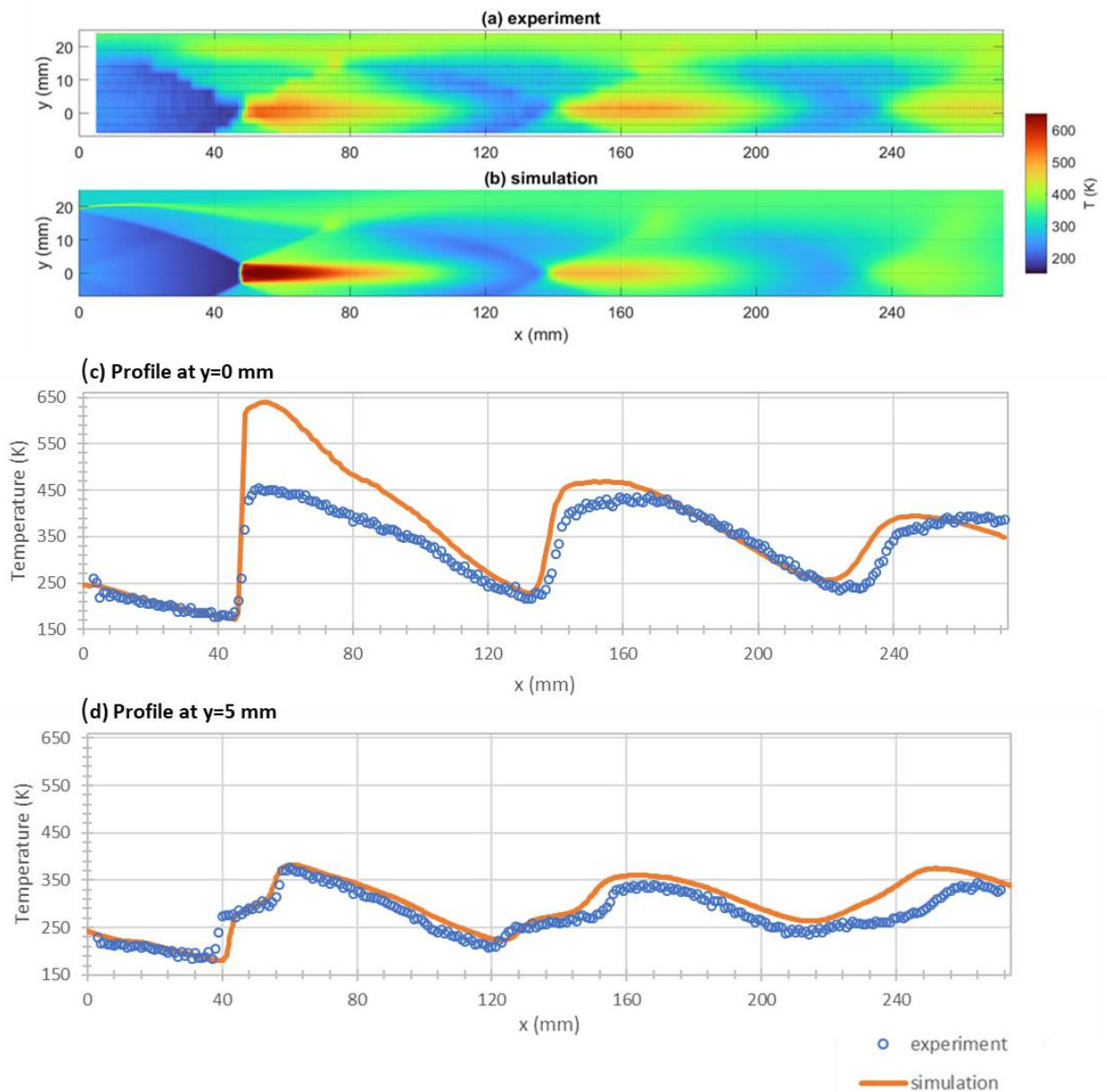


Figure. 3 (a) Experimental temperature map obtained in the XY plane intersecting $z=0$ mm concatenating horizontal profiles (scan performed parallel to the direction of the flow), and (b) LES simulated map. (c, d) Experimental (blue circle) and simulated (orange line) temperature profile (c) performed at $y=0$, (d) performed at $y=5$ mm.

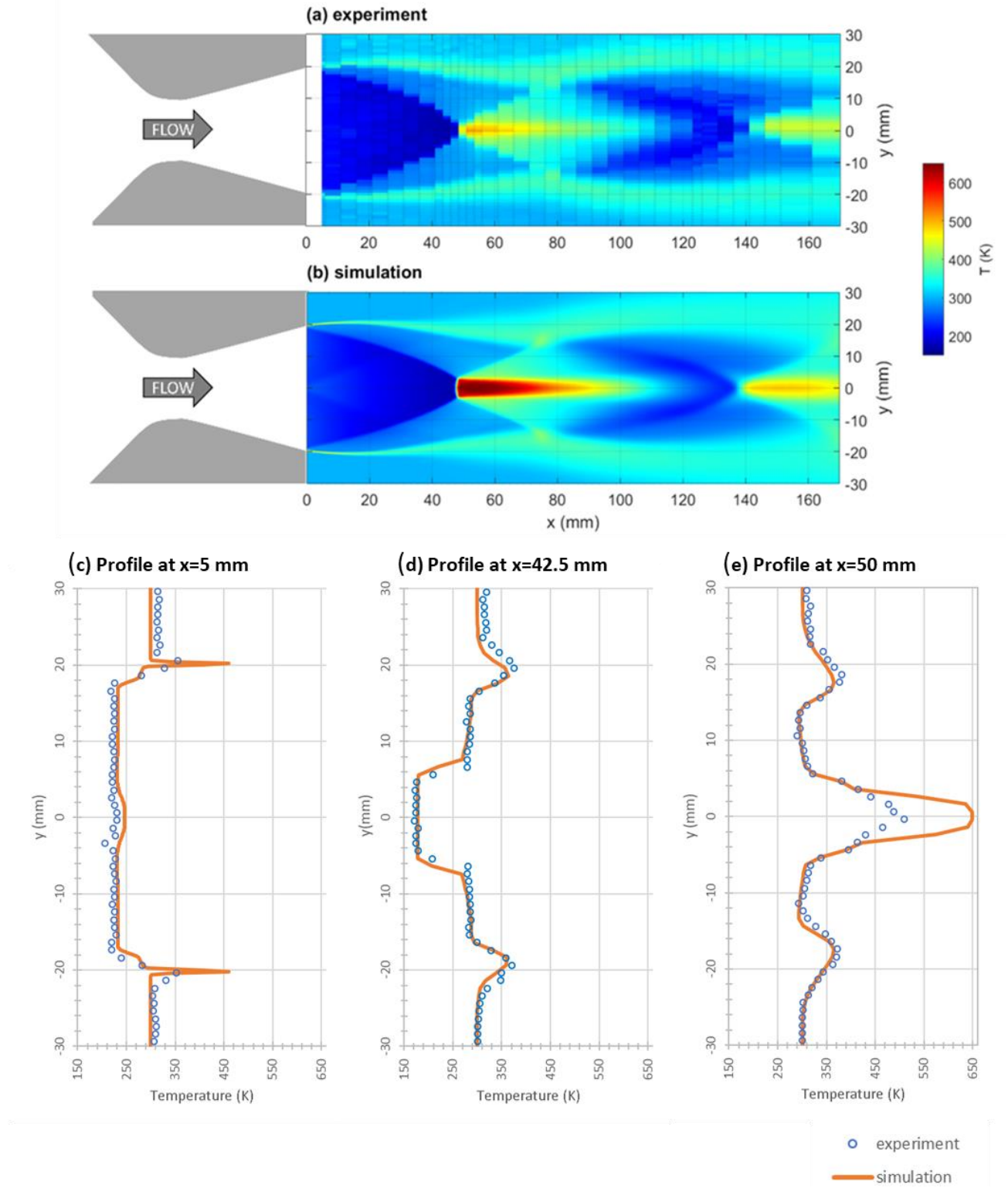


Figure. 4 (a) Experimental temperature map achieved in the XY plane intersecting $z=3$ mm in the vicinity of the first shock cell by concatenating vertical profiles (scans performed perpendicular to the flow direction), and (b) LES simulation. (c, d, e) Experimental (blue circles) and simulated (orange lines) temperature profiles obtained at (c) $x=5$ mm, (d) $y=42.5$ mm, and (e) $x=50$ mm.

4. Conclusions

In conclusion, rotational RS thermometry has been successfully applied to a round free-stream supersonic heated air jet. A state-of-the-art precision of $\sim 0.3\%$ in ambient air was obtained using signal accumulation over 1 s, and allowing to build temperature maps in the range 150–600 K with a $1\text{ mm} \times 2.5\text{ mm}$ spatial sampling over a large area ($\sim 100\text{ cm}^2$). The experimental 2D maps showed overall good agreement with LES simulation revealing the precise structure of the flow in different planes of interest. To the best of the authors' knowledge, the temperature mapping presented in this work is unprecedented in terms of both spatial resolution and measurement coverage, enabling the detailed reconstruction of multiple shock cells topology.

These measurements demonstrate the capability of the RS technique to deliver quantitative diagnostics in supersonic jets and to build reliable databases for LES model validation. They also confirm the robustness of the experimental setup under harsh conditions, including high acoustic noise levels. Experimental measurements revealed some limitations of the simulated flow structure downstream the first Mach disk, whose temperature appears overestimated by the model. Further analysis will be carried out to elucidate these observed discrepancies between experimental and simulated temperature, in particular by correlating those results with velocity maps measured by PIV and FLEET techniques.

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