Coherent Anti-Stokes Raman Spectroscopy (CARS) Measurements in Supersonic Combustors at NASA Langley Research Center

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ABSTRACT

This paper describes the recent use of coherent anti-Stokes Raman spectroscopy (CARS) to study supersonic combustion at NASA Langley Research Center. CARS is a nonlinear optical measurement technique used to measure temperature and species mole fractions remotely in harsh environments. A CARS system has been applied to two different combustor geometries at NASA Langley. Both experiments used the same vitiated wind-tunnel facility to create an air flow that simulates flight at Mach numbers of 6 and 7 for the combustor inlet and both experiments used hydrogen fuel. In the first experiment, the hydrogen was injected supersonically at a 30-degree angle with respect to the incoming flow. In the second experiment, the hydrogen was injected sonically at normal incidence. While these injection schemes produced significantly different flow features, the CARS method provided mean temperature, N_2, O_2 and H_2 maps at multiple downstream locations for both. The primary aim of these measurements was to provide detailed flowfield information for computational fluid dynamics (CFD) code validation.

INTRODUCTION

Supersonic combustion ramjet (Scramjet) engines present significant challenges for engine designers using computational fluid dynamics (CFD) codes. Supersonic combustion is characterized by turbulent, unsteady flow, flow separation, compressibility effects, shock-shock and shock-boundary layer interactions, highly 3-dimensional flow, fuel-air mixing, and finite-rate chemistry. Ideally CFD codes would predict these phenomena as well as laminar-to-turbulent transition, fuel ignition, and engine unstart. However, existing CFD codes do not capture many of these effects accurately. Simplified models are implemented in the codes for computational efficiency and because, in some cases, more rigorous models do not exist. Despite the limitations of these codes, they are being used to design the next generation of scramjet engines. High-quality benchmark data is required to validate these codes so that the codes can be used with confidence or with caution, as appropriate. This paper summarizes such experiments for CFD validation performed at NASA Langley Research Center in which the dual-pump coherent anti-Stokes Raman spectroscopy (CARS) technique was used to map the temperature and species mole fraction in two different supersonic combustor geometries.

CARS is an optical measurement technique that can instantaneously and simultaneously measure temperature and multiple species mole fractions in combustion environments. Measurements are made in about 10-ns within a small volume of about 1.5 mm x 0.2 mm x 0.2 mm, typically and measurements are typically uncorrelated in time, since the lasers operate at about 10-Hz and for supersonic flows, very large volumes of fluid pass the measurement region in the 100 ms between laser pulses. The references cited below provide much more detailed descriptions of these experiments, the experimental techniques and analysis methods used, and the results.

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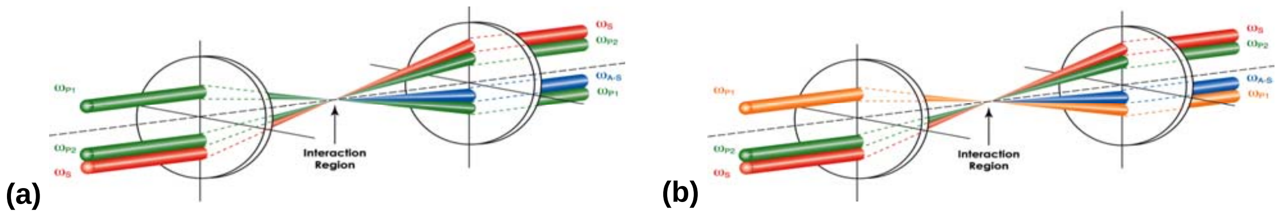

Figure 1: CARS approaches: (a) broadband CARS, for probing N_2 [Ref. 1], (b) dual-pump CARS, for probing N_2-O_2-H_2 [Ref. 4]. These figures show the planar BOXCARS phase matching geometry.[1]

CARS Measurement Technique

In the most commonly-used CARS approach, two collimated green laser beams derived from the same Nd:YAG laser form the *pump* beams as shown in Figure 1(a). One collimated red beam from an Nd:YAG-pumped dye laser forms the *Stokes* beam. The pump and Stokes beams are directed through a spherical lens that crosses and focuses the three beams at a point as shown in the figure. A Raman interaction between these three laser beams and the gas present in the beam-crossing volume generates a blue signal beam, known as the *anti-Stokes* beam. If the Stokes laser has a broadband spectrum then the anti-Stokes beam is also broadband. In this case, the anti-Stokes beam can be dispersed with a spectrometer onto a CCD camera and the Raman spectrum is acquired in a single laser pulse. This method is known as *broadband CARS.*[1] Commonly, the frequency difference between the green and red beams is chosen to probe Raman transitions in N_2. Alternately, a different laser dye can be used in the Stokes laser to probe other molecules, such as O_2. An example of the N_2 CARS spectrum is shown in Figure 2. The N_2 spectrum contains both rotational and vibrational spectral features, each having different ground-state energies. The shape of this spectrum is very sensitive to the gas temperature since the gas temperature dictates the distribution of molecules among these states. At low temperatures, the higher energy level states (to the left of the figure) are unpopulated whereas at high temperatures these states are populated. These population distributions determine the shape of the spectrum, so one can determine temperature by measuring this spectrum. Additionally, the magnitude of the anti-Stokes signal from N_2 is related to the mole fraction of N_2, though additional information is required to precisely determine N_2 mole fraction from such a spectrum.

The broadband N_2-CARS method described above was used at NASA Langley Research Center for supersonic combustion tests in the early 1990's[2] and then again in 2000-2001[3]. These tests were successful, but variations of the CARS technique were sought after to obtain additional information about species mole fractions. Several variations have been developed that have enhanced the basic broadband-CARS method.[1] In H_2-air combustion systems, it is useful to measure temperature, N_2, O_2 and H_2.[4] These parameters have been measured in the current paper using the *dual-pump CARS* method. Dual-pump CARS was first developed by Robert Lucht and coworkers.[5]

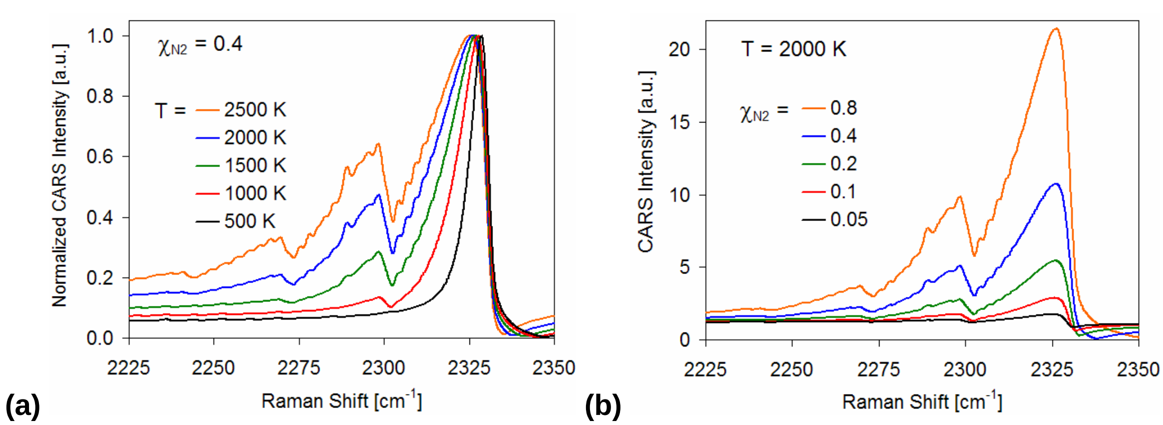

Figure 2: N_2 CARS Spectra calculated from the Sandia CARSFIT code[7], illustrating (a) temperature sensitivity, while N_2 mole fraction is held constant, and (b) N_2 concentration sensitivity, while temperature is held constant. Calculated at 1 atmosphere.

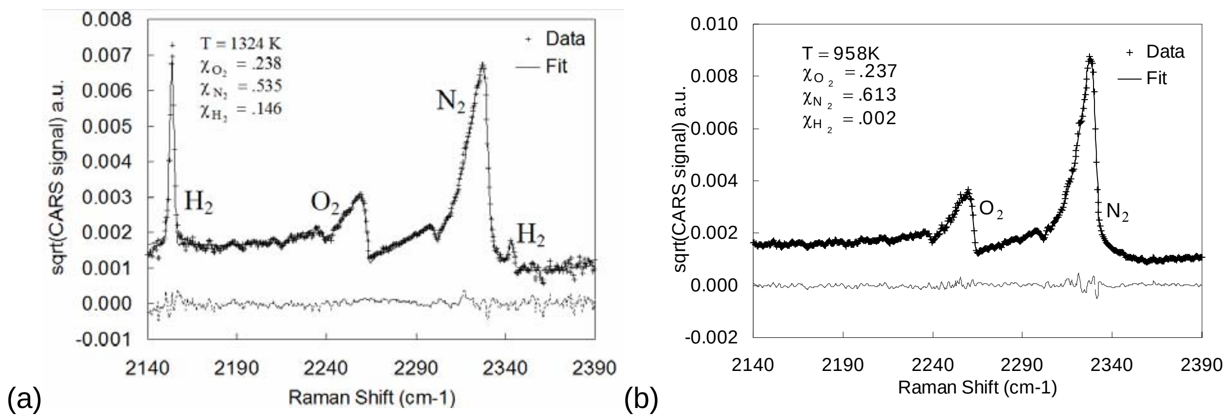

Figure 3: Measured single-shot dual-pump N_2-O_2-H_2 CARS spectra and best fits, measured (a) downstream of fuel injection and (b) upstream of fuel injection.

Dual-pump CARS is a variation on the broadband CARS scheme described above in that a narrowband, tunable, pump beam replaces one of the green pump beams. The color of this pump laser is chosen so that the frequency difference between it and the broadband Stokes laser corresponds to the Raman shift of one molecule of interest, such as O_2. As before, the color of the Stokes laser is chosen so that the frequency difference between it and the first (green) pump beam corresponds to the Raman resonance in the other molecule of interest, e.g. N_2. This technique has several merits. Importantly, the two anti-Stokes spectra resulting from the two different species occur at nearly the same wavelength, despite having vastly different Raman shifts, so that they appear side by side at the exit of a spectrometer and can be acquired by a single CCD camera. The separation on the detector between the spectral lines probed by the two pump beams can be varied by changing the wavelength of the tunable pump laser, allowing overlaps between spectral features from the two pump beams to be avoided. This feature of dual-pump CARS simplifies the setup compared to other approaches that require multiple cameras and spectrometers. Another merit is that the same three lasers are involved in generating the two signal beams. Thus, there is a very high degree of correlation between the relative intensities of the two measured spectra. Consequently, laser-energy measurements and relative detector calibrations (and their resulting uncertainties) are not necessary with this method. Another merit when applying dual-pump N_2-O_2 CARS to study H_2 combustion is that there are several pure rotational H_2 lines coincident with the N_2 and O_2 spectra.[4] Thus N_2, O_2, and H_2 can simultaneously be measured along with temperature. This is the approach taken at NASA Langley Research Center to study supersonic combustion.[4,6] This setup uses a frequency-doubled 532 nm (green) Nd:YAG laser for one pump beam, a 555 nm (yellow) narrowband Nd:YAG-pumped dye laser for the second pump beam and a broadband 607 nm (red) laser for the Stokes beam. The anti-Stokes signal is generated at 491 nm (blue). This arrangement is shown in Figure 1(b). Typical spectra obtained from this system are shown in Figure 3.

Experimental Test Hardware and Procedure

Test hardware for the present experiments was chosen to be representative of the flow typical in scramjet engines.[3] A vectored fuel-injection configuration was first tested.[4] Subsequently a normal-fuel injection case was tested.[6] The geometry of both fuel-injection configurations is shown in Figure 4. The tests were performed in Langley's Direct Connect Supersonic Combustion Test Facility, which is a combustion-heated (hydrogen vitiated) facility. The facility heater was operated at a temperature simulating Mach 7 flight for the vectored-injection case and Mach 6 flight for the normal-injection case. In both cases, a converging-diverging nozzle was mounted at the end of the heater, providing Mach 2 flow into the supersonic combustion duct. In both cases, the duct consisted of two sections: a copper upstream duct and a steel downstream duct. In the vectored-injection case, unheated hydrogen fuel was injected supersonically at Mach 2.5 at an angle of 30 degrees with respect to the incoming flow in the copper duct. The fuel/air equivalence ratio was 1. In the normal-injection case, unheated hydrogen fuel was injected sonically normal to the flow from the top wall, as shown in the figure. The equivalence ratio for this case was 0.7. Both copper and steel ducts had a 3-degree divergence angle on the top wall and a horizontal bottom wall. The side

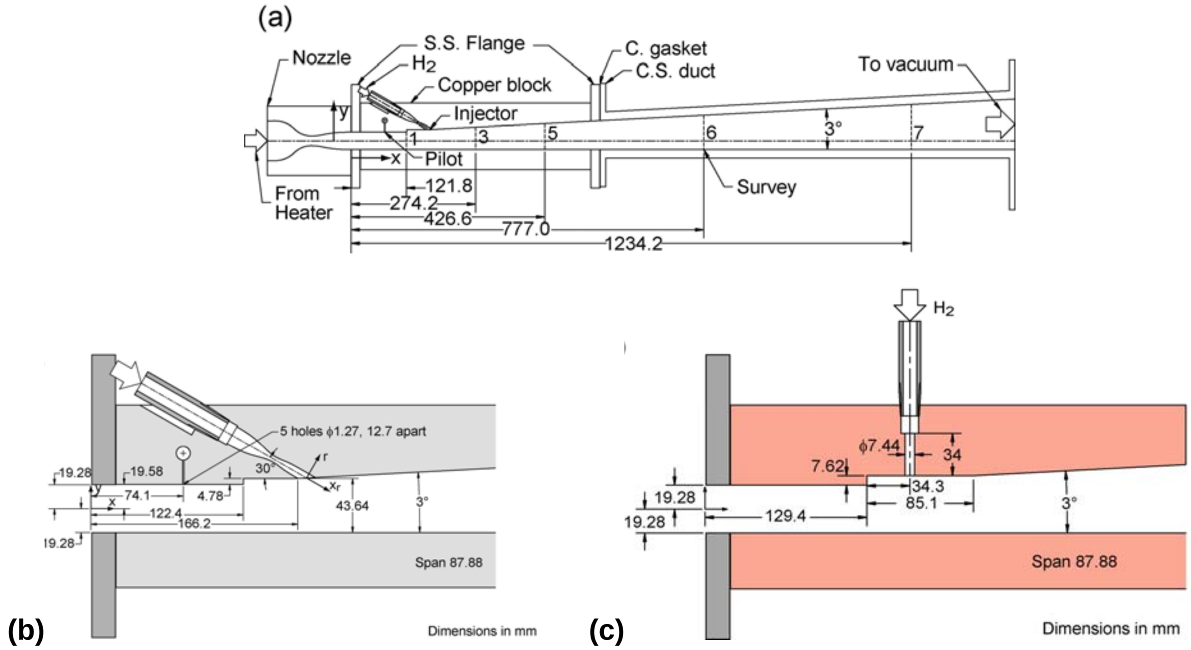

Figure 4: Test configurations for supersonic combustion test hardware: (a) full schematic showing the facility nozzle (far left), copper (left) and steel (right) ducts for the vectored-injection experiment and (b) close-up of the injection region for the vectored-injection experiment. Also shown is (c) close up of the injection region for the normal-injection experiment, which is otherwise the same as (a). Five windowed measurement ports are indicated in (a) by numbers (1, 3, 5, 6, and 7).

walls were parallel to each other. These ducts were equipped with slotted windows on the sides to pass the CARS laser beams. The test hardware was uncooled, so the test time was limited to about 20 seconds per run, with ~15 minutes of cool down time required between runs. Approximately 20 runs could be performed per day. The laser operated at 10 Hz. Thus, approximately 4000 measurement points could be obtained per day. A periscope system allowed the CARS measurement volume to be moved around in the flow, allowing a single spanwise plane in the flow to be mapped each day. The CARS spectra were analyzed with a NASA-Langley-modified version of the Sandia CARSFIT code.[7] Then, response surfaces were fit to the measured data to produce the resulting temperature, N_2, O_2 and H_2 mole fraction maps.[8] Wall pressure profiles and heat transfer measurements inferred from wall-mounted thermocouples were also measured, but are reported elsewhere.[3]

RESULTS OF VECTORED-INJECTION EXPERIMENT

Figure 5 shows the results of the vectored-injection experiment. These images show a cut-away view of the 5 planes measured in the duct. Flow is from top left to bottom right. The fuel was injected from the top wall between planes 1 and 3. Temperatures are in Kelvin and species measurements are in mole fraction. While we believe that the temperature, N_2 and O_2 measurements are accurate, there is a known 10-15% systematic error in the H_2 measurements, so these should be considered qualitative. The maps show that the temperature of the gas entering the combustor was relatively uniform and close to the temperature predicted for these facility-operating conditions. The N_2 and O_2 maps, on the other hand, show a slight left-to-right non-uniformity of the composition entering the combustor. However, it is curious that this left-to-right non-uniformity is not corroborated by other evidence, such as a temperature non-uniformity. In plane 3 the fuel jet appears in all four maps: the temperature, N_2, and O_2 mole fractions decrease while the H_2 mole fraction is relatively high. In plane 5, the fuel jet has increased in size and has penetrated closer to the bottom wall. However the gas around the fuel jet has remained close to the inlet temperature. Significant combustion has occurred by plane 6, as evidenced by the increase in temperature and decrease in O_2 mole fraction. Combustion continues to occur at least until plane 7, where the temperature is still higher and O_2 mole fraction still lower. However, the H_2 maps show evidence of tens of percent of unburned hydrogen in plane 7. Unburned O_2 also exists in this plane, but it has not mixed with the available H_2.

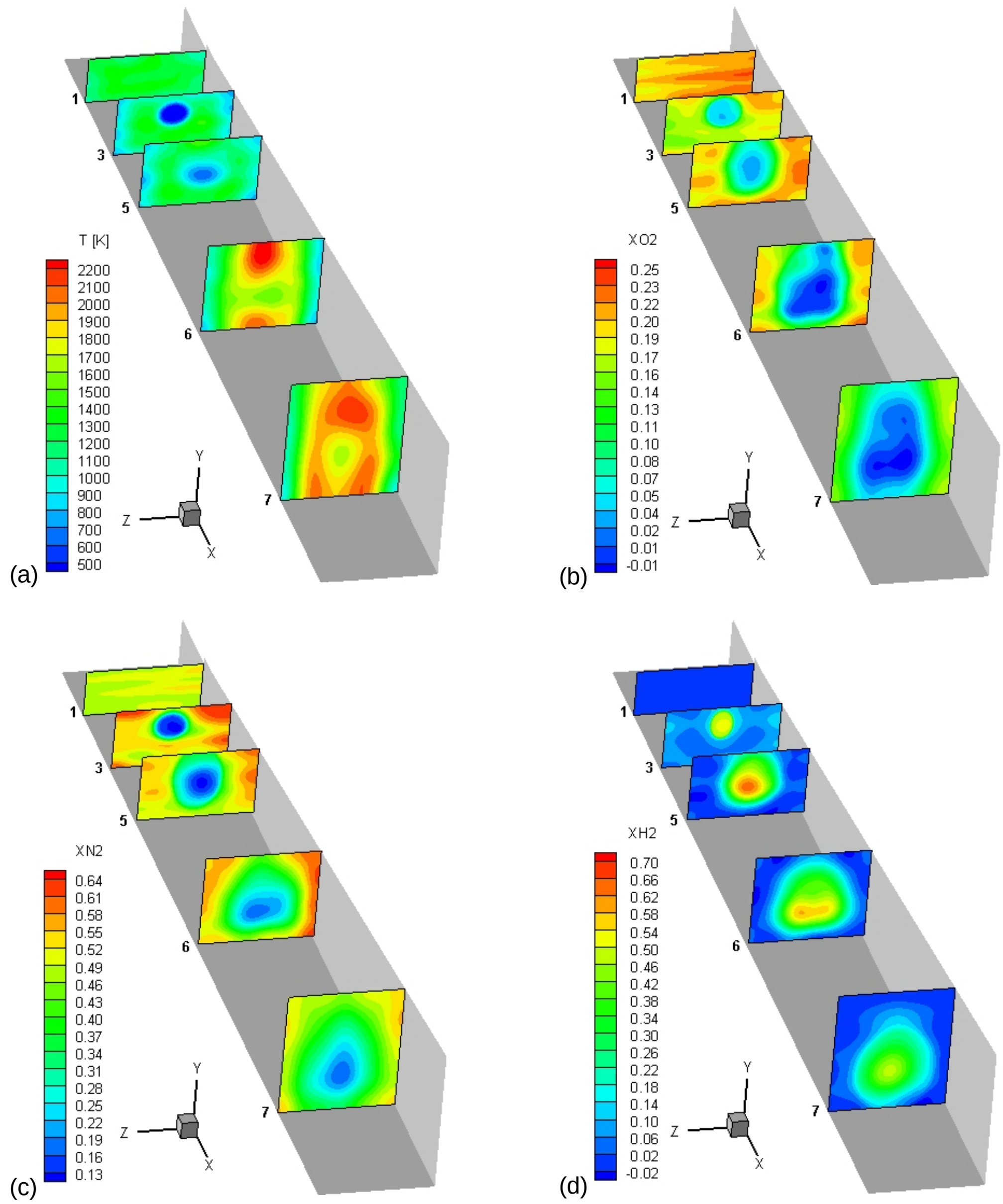

Figure 5: Maps of (a) mean temperature in Kelvin, (b) mean O_2 mole fraction, (c) mean N_2 mole fraction, (d) qualitative mean H_2 mole fraction at Mach 7 enthalpy for the vectored-fuel-injection case (Refs. 4 and 6).

An interesting outcome of this experiment was the observation of delayed ignition: combustion appears to be inhibited until after plane 5. The prediction of ignition delay in this type of flow, in which the flame is not attached to the injection point or a bluff surface, is very difficult since it very sensitive the models contained within the CFD codes, including models for turbulence and chemical kinetics. Thus, the experiment proved to be a very challenging case for CFD simulations. At present, 8 different research groups around the world have requested this data set for comparison with their CFD codes. One published CFD comparison with this data set[9] could not simultaneously reproduce measured wall-pressures, CARS-measured temperature maps and jet penetration visualizations provided by CARS. These discrepancies could either point to deficiencies in the codes or to deficiencies of the measurement techniques to accurately characterize the flowfield, such as measurement of the inflow conditions including turbulence intensities. Additional CFD simulations of the flowfield and additional detailed experimental data, particularly velocity measurements, are required to resolve these modeling issues.

RESULTS OF NORMAL-INJECTION EXPERIMENT

Figure 6 shows the results of the normal-injection supersonic combustion experiment. The plane 1 measurements again show a uniform temperature distribution and a slight left-to-right increase of both O_2 and N_2 mole fraction. The H_2 jet first becomes visible in plane 3, increasing in mole fraction from 0.0 around the outside of the fuel jet to a maximum of 0.7 in the center of the duct (though caution should be used in interpreting the H_2 measurements as described above). This plane also shows strong indications of combustion occurring along the top of the duct, where the temperature increases to a peak value of approximately 1600-1700 K. This also corresponds to a region of reduced ratio of O_2 to N_2 on the top of the duct, to the outer sides of the fuel, indicating consumption of O_2 by combustion. The fact that combustion is already occurring in plane 3 for the normal-fuel-injection case is of interest because, as seen in Figure 5, significant combustion for the vectored-fuel-injection case doesn't occur until after plane 5. It is likely that the subsonic region of flow generated by the normal fuel injection acts as a flame holder, whereas the supersonic vectored injection does not flame-hold in this manner. The stronger bow shock generated by the normal injection will also increase the temperature of the flow compared to the vectored-injection case, reducing the ignition delay time.

Comparison of the mean O_2 distributions in Figures 5 and 6 shows that, in the vectored-injection case the O_2 in the central part of the duct was fully consumed by the time the flow had reached plane 7, whereas excess O_2 was still noticeable at plane 7 for the normal-injection tests. This result is consistent with the lower equivalence ratio of the normal injection case, which leads to a more rapid increase in the oxygen fraction (either molecular or consumed by reaction) in the plume. Another explanation of the depletion of O_2 in the center of the duct is the effect on mixing of the direction of the fuel injection. The direction of injection relative to the freestream gas in the vectored-injection case causes less shear forces than the normal-injection case and therefore less mixing is initiated at injection than in the normal-fuel-injection case.

Once the flow reaches plane 6, N_2 is somewhat uniform across the plane indicating that air has penetrated to the center of the fuel jet. However, there continues to be an O_2 deficit near the center of the fuel jet. In this same location, temperature has risen above 2000 K. In comparison, for the vectored case at plane 6, the temperature at the center of the fuel jet is only ~1500 K and the O_2 mole fraction is approximately zero at the center of the H_2 plume. This is further evidence that the gases appear to be mixing more completely in the normal-injection case. In the vectored case there is more H_2 present in plane 6 than for the normal case because of the poorer mixing and later start of combustion.

In plane 7 of the normal injection case only a small amount (~12%) of H_2 remains and the N_2 is almost completely uniform. By contrast, the vectored case shows relatively more H_2 in plane 7 indicating less mixing of the gasses within the duct.

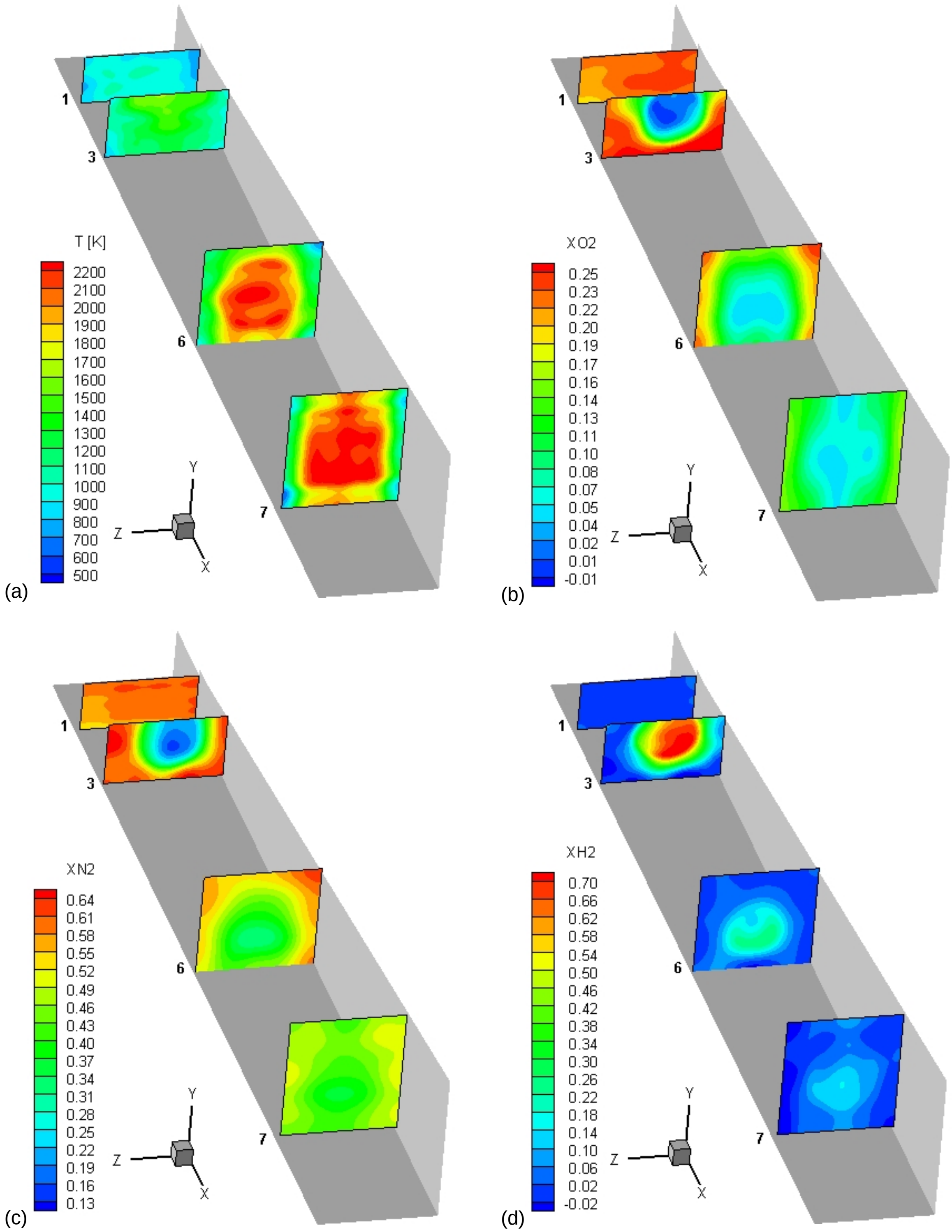

Figure 6. Plots of (a) mean temperature (b) mean O_2 mole fraction, (c) mean N_2 mole fraction, (d) mean H_2 mole fraction at Mach 6 enthalpy for the normal fuel injection case.

CONCLUSIONS

We have used the dual-pump CARS measurement technique to simultaneously measure temperature and the mole fraction of N_2, O_2 and H_2 in two different model supersonic combustor configurations. This paper has presented the mean maps of these parameters in vectored-fuel-injection and normal-fuel-injection combustors. In addition to these data, the referenced work contains maps of the RMS fluctuations of the various parameters, and the correlations between the different parameters. All of these data provide a wealth of test cases for comparison with CFD codes.

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