CARS temperature measurements in turbulent and supersonic facilities

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This paper documents the development of the National Aeronautics and Space Administration's (NASA) Langley Research Center (LaRC) Coherent AntiStokes Raman Spectroscopy (CARS) systems for measurements of temperature in a turbulent subsonic or supersonic reacting hydrogen-air environment. Spectra data provides temperature data when compared to a precalculated library of nitrogen CARS spectra. Library validity was confirmed by comparing CARS temperatures derived through the library with three different techniques for determination of the temperature in hydrogen-air combustion and an electrically heated furnace. The CARS system has been used to survey temperature profiles in the simulated flow of a supersonic combustion ramjet (scramjet) model. Measurement results will be discussed.

INTRODUCTION

Measurements in aerodynamic research tunnel facilities have typically been limited to flow visualization, surface measurements, and intrusive flow-field measurements using probe-based techniques. Scramjet (a name coined from the combination of supersonic combustion ramjet) research introduced new measurement requirements and constraints. The heat and dynamic pressure of the high enthalpy flow of a scramjet model make probe measurements difficult. In some cases, the heating rate can be so high that probe survival becomes an issue. Thus, nonintrusive measurements, made possible with laser-based techniques, became attractive. In the late 1970's and early 1980's at NASA LaRC, a nonintrusive diagnostics program development focused on CARS because the system showed promise for working in the combustion tunnel environment.

NASA LaRC has an ongoing program concentrated on understanding supersonic combustion fundamentals and development and testing of propulsion concepts. Research facilities include test cells which provide supersonic flow with enthalpy adequate to simulate a significant portion of the flight envelop of air-breathing scramjet powered vehicles. The apparatus(1) provided the required total temperature and pressure by burning hydrogen in air. The oxygen which was consumed was replaced so that the flow would consist of what was termed vitiated air. The goal of the nonintrusive diagnostics work was to obtain measurements in the hostile environment of the test cell. Many problems were addressed during the development of the CARS system including limited physical and optical access, high noise levels, and temperature excursions during testing. A series of increasingly complex tests was conducted to validate the CARS system for this hostile environment . These tests included: 1. a premixed hydrogen-air "flat flame" burner, which was well instrumented and characterized; 2. a subsonic turbulent-diffusion burner to provide a time-varying combustion source; 3. a laboratory-scale supersonic turbulent-diffusion burner to provide experience with reacting flow with shocks; and 4. a scramjet combustor installed in a test cell. The paper will discuss the fundamentals of the CARS system as it was developed and the details of the combustion sources, and finally present representative data from some of the tests. More complete details of the work described may be found in other publications (2-8).

DESCRIPTION OF CARS

CARS is a nonlinear process which uses two (or more) lasers to produce a signal from which temperature and density of the probed species may be determined. A good review of CARS fundamentals is given by Eckbreth (9). In the following sections, the theoretical background of CARS and the arrangement of the hardware as used at NASA LaRC will be briefly reviewed.

Theoretical Background

CARS signal generation has been presented previously in the literature (10-17) and, therefore, will only be briefly reviewed here. A signal generated by a CARS system contains information related to the temperature and density of the probed molecule. The total intensity of the signal is related to the density, while the spectral distribution of the intensity is related to temperature. In this paper, only the temperature information will be presented.

To generate a CARS signal, three photons of selected frequency (energy) interact with a chosen molecule to produce a fourth (signal) photon. There is some freedom in the selection of the source for the two photons at frequency ω_1. The source must meet the short-pulse requirements (10 ns) imposed by the high velocity, turbulent flow that is to be measured. These ω_1 photons also must be energetic enough to excite a molecule to a level above the naturally-occuring rotational-vibrational states above the ground state. A pulsed, doubled Nd:YAG laser meets these criteria. The third photon at frequency ω_2 must be chosen such that the energy difference between the two photons at ω_1 and ω_2 is equal to the normally populated rotational-vibrational levels in the molecule of interest. If the laser providing ω_2 is broad-band, all the energy levels of the molecule can be simultaneously interrogated. The ω_2 photons interact with the molecule excited to a lower virtual state by ω_1 photons to force population of the rotational-vibrational states allowed by the

temperature of the molecule. A second interaction with an ω_1 photon elevates the molecule to an upper virtual state. Natural decay to the ground state yields a signal photon at frequency ω_3. Thus, a single laser pulse of short duration can generate a signal containing all the temperature information from the probed volume in a single pulse. This characteristic is important when the probed medium is a turbulent supersonic reacting mixture of gases. In the cited references, additional momentum and polarization criteria are discussed. These criteria must be satisified for efficient signal generation and for some density measurement schemes.

CARS Temperature Measurement

The spectral distribution of intensity of the CARS signal varies with temperature (18) due to the temperature-dependent population difference between the states. The spectral shape as a function of temperature can be analytically predicted. Factors such as spectrograph slit function, dispersion and resolution must be considered in the spectral calculations. In the general case, other variables such as the gas composition must be included in the calculation. Such considerations are important since a CARS signal consists of both the resonant signal from the species being probed and the nonresonant signal from other species which are present.

To determine temperature with a CARS system, a spectrograph is used to spectrally disperse the signal. Each signal is detected by an intensified linear photodiode array. By comparing the resulting CARS spectrum with the predicted spectra, the temperature of the sampled gas may be determined.

One of two approaches may be selected to implement the actual temperature determination. The first approach involves iteration of the composition and temperature chosen for the analytical calculations while comparing with laser-generated CARS spectra. As this approach is computer-intensive, an hour may be required to determine a single temperature. A second approach, which was used with this system, is to calculate a library of spectra with assumed composition and variable temperature, then perform a least-squares fit of CARS data to these predicted spectra. While several hours (dependent upon computer speed) may be needed to calculate the library, a least-squares fit of the laser-generated data to the library to yield a temperature measurement can be performed at a rate of approximately one per second. Fig. 1 shows a graphical representation of a least-squares fit of a CARS laser-generated spectrum to one of the predicted spectrum in the library. The validity of the analytically predicted library approach was confirmed by comparing the temperature (as measured by the CARS system) with two calibration sources. Independent assessments of temperature for the two sources were used for the comparison.

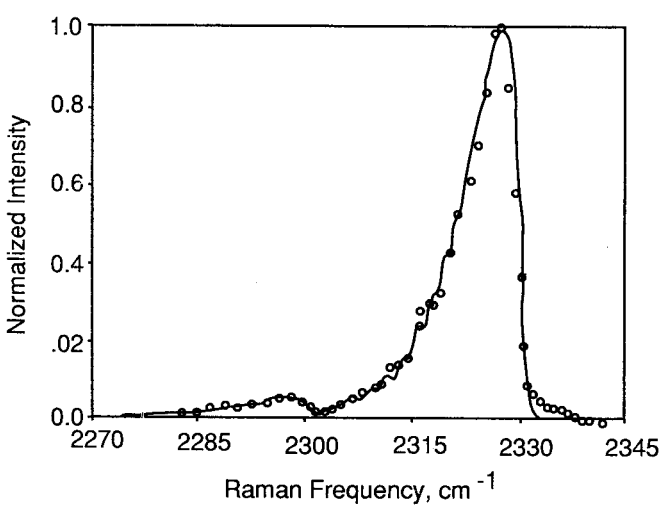

Fig. 1. Least-squares CARS data fit to an analytically predicted spectrum from the predicted library of spectra.

CARS Test Cell Hardware

To adapt the CARS system to operate in the harsh environment of the test cell, several features were necessary: 1. capacity for traversing the CARS sample volume, 2. options for coping with thermally induced distortions of the optical system, 3. potential for laser ignition of hydrogen in the event of a leak, 4. remote operation of flags to attenuate or block signal or laser beams, and 5. efficient coupling of the signal to the spectrometer-detector. The general arrangement of the optical components on the optical platform of the CARS system is shown in fig. 2 The support structure for the CARS optical components was assembled from lengths of optical rails and connector cubes. The structure was assembled to provide two surfaces, a 1.22 X 2.44 m (4 X 8 ft) optics pallet on top and a lower surface for the Nd:YAG laser, dye pumps, and other non-optical components. An enclosure was constructed around the complete assembly. The enclosure was "U" shaped to accommodate the duct containing the supersonic flow. A positive pressure was applied to the housing to prevent the deposition of dust from the test cell on the CARS system optics. In addition, the air flow prevented the accumulation of hydrogen in the box – an important consideration as high energy laser beams or electrical components could ignite any stray hydrogen. Initially, sound absorbing material was considered to reduce the noise environment and air supports were provided to isolate vibrations transmitted through the floor, however, both of these improvements were found to be unnecessary.

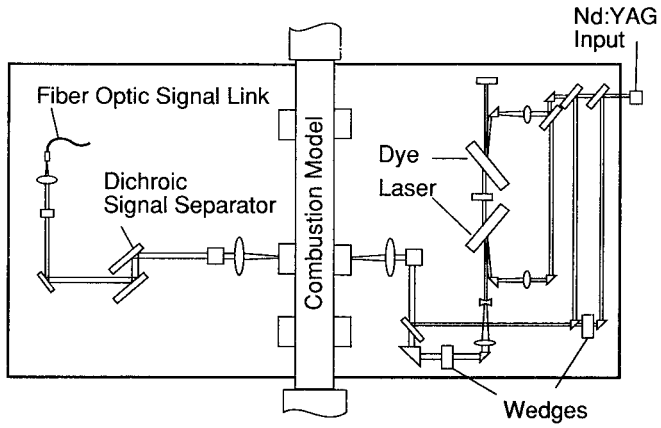

Fig. 2. Schematic of the CARS optical system installed in Hypersonic Propulsion Test Cell 2.

A Nd:YAG laser provided 200 mJ, 532 nm, 10 Hz, horizontally polarized, 10 ns pulses through a system of prisms to the pallet surface. At that point, as can be seen in fig. 2, the Nd:YAG laser was split into three parts. One part was used to pump a broadband dye laser centered about 606.5 nm as required for the CARS system to interrogate nitrogen. The two ω_1 beams (provided by the Nd:YAG Laser) and the ω_2 beam (provided by the dye laser) were brought through a set of prisms to a lens mounted on two translation stages. The components mounted on the translation stages provided movement of the CARS sample volume (the common focal volume of the three laser beams) in a plane perpendicular to the supersonic reacting flow. The beams were arranged in the planar BOXCARS configuration with the

beams in a vertical plane. The focusing and recollimating lenses had 28 cm focal lengths. The interaction length for this arrangement was found to be 0.8 mm (.032 in) in length at half maximum and the interaction volume was estimated to be about 50 microns (0.002 in) in diameter.

Movement of the interaction volume and adjustment of the beam crossing were under computer control. The focusing and recollimating lenses and four turning prisms were mounted on translation stages which were driven by stepper motors. This arrangement allowed the CARS interaction volume to be moved in a plane perpendicular to the flow in the duct. Initial alignment of the CARS ω_1 and ω_2 beams was performed by manual adjustments of optical elements in the individual beam paths. "Fine tuning" of the crossing and adjustments after the test cell was closed were made using two pairs of two degree optical wedges mounted in the optical path of one ω_1 and the ω_2 beam as shown in fig. 2. These wedges were independently rotated by computer-controlled stepping motors.

The test cell is a hostile and cramped environment; therefore all possible equipment was remotely located. An optical fiber was used in a manner similar to the technique used by Eckbreth (19) to couple the CARS signal from the test cell to the control room where the spectrometer and reticon were located. Fig. 2 shows some of the details of the hardware used to couple the CARS signal into the fiber. Using the suggestion of S. Fujii (20), a pair of dichroic mirrors was used to separate the ω_1 laser and ω_2 energy from the ω_3 (signal) beam. For simplicity, one reflection of the signal and CARS laser beams is indicated on each of the mirrors of the dichroic signal separator (four reflections were arranged on each of the two mirrors). A maximum of 92 percent of the signal energy (based on signal reflection > 99 percent per surface) could be presented to the microscope objective for focusing into the optical fiber. The net first surface reflection of the ω_1 through the dichroic separator was calculated to be 10^{-8} of the incident energy (based on ten percent reflection per surface). The 50 μm fiber was chosen as a compromise between the desire for a large fiber on the collection end to improve coupling efficiency and a small fiber on the output end to minimize the image width at the spectrometer. A twenty meter fiber carried the signal out of the test cell to the detector.

Fig. 3 shows the components used to couple the CARS signal from the output end of the fiber to the spectrometer. At the spectrometer, a combination of cylindrical lenses was used to focus the CARS signal into a line image in the entrance slit. With the indicated combination of cylindrical lenses (21), the focus of the horizontal lens was in front of the entrance slit while the focus of the vertical lens was in the entrance slit. To match the image height to the detector height, the height of the focused signal beam was matched to the 2 mm height of the reticon detector. As signal intensity varied with density, dynamic range enhancement was provided with a signal splitting device similar to that of Eckbreth (22); this application differed in that the signal splitter was placed immediately in front of the spectrometer. The entrance slit was turned horizontally to accommodate the two images. Two images of the signal were formed at the entrance slit with the intensities differing by an order of magnitude. When the data were processed, the larger signal that did not exceed full scale was processed. Note that the spectrometer slit function was optically determined by the focusing characteristics of the cylindrical lenses rather than by a physical slit.

Remote operation of the CARS system required certain beam blocking and attenuation functions to be remotely performed. Part of this requirement was established by the necessity to operate the laser continuously to minimize "drift."

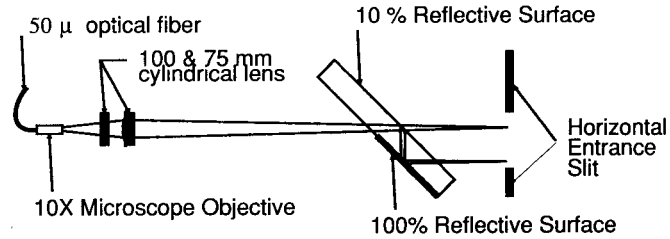

Fig. 3. Optics for coupling the CARS signal from the light fiber to the spectrometer. The input to the fiber is shown in fig. 2.

Switches were devised to allow computer control of two beam blocks, an optical attenuator, and the air activated "seal" on the window. These switches operated 45 degree rotating solenoids or solenoid-operated valves. Beam blocks were provided in the output of the Nd:YAG laser and in the ω_2 beam. A one percent transmission filter could be inserted into the ω_3 beam to attenuate the strong CARS signal generated in air. Thus, the signal could be monitored as the system was remotely tuned with the rotating wedges. Light that was not related to the CARS signal was measured by inserting a beam block in the ω_2 beam and collecting 100 data points for use during data processing as a "tare" correction. For reacting flow temperature measurements, the window seal was opened, the tunnel was started, the main beam block was removed, and 20 CARS data points were collected. The sample volume was then moved and another 20 points were collected. At the end of the data sequence, the beam block was replaced and the window seal was closed.

One of the calibration devices used with the CARS system was a flat flame (porous metal plug) burner through which premixed hydrogen and air flowed. At high temperature, the plug functioned as a flame holder. At a fuel equivalency ratio less than approximately 0.5, corresponding to a temperature of approximately 1300 K, the flame front lifts off the plug and becomes unstable. Thus, the flat flame burner was a reliable calibration device only if the flame was in the attached mode. The instrumentation for the burner allowed measurement of air, hydrogen, and water flow rates. From these measurements two parameters, Φ and heat loss fraction could bd calculated. Φ is the stoichiometric fraction and the heat loss fraction is portion of the hydrogen energy lost to the cooling water. The post-flame conditions for fuel-lean combustion were calculated as a function of Φ and heat-loss fraction using the technique of Gordon and McBride(23) . Two techniques (discussed in ref. 2), sodium-line reversal and radiation-corrected thermocouples, were used to verify the applicability of the model in the post-combustion zone. Software was written to monitor the operation of the burner and display temperature and other values interpolated from the combustion model.

For temperatures lower than those that the calibration burner could provide, a baffled tube in an electrically-heated furnace was used. The baffles minimized convection losses from the central heated chamber which was sampled with the CARS system. The temperature of the measurement volume in the tube was monitored by a thermocouple. Since radiation from the thermocouple was blocked by the heated walls of the tube, no radiation correction was necessary.

CARS in the Test Cell

Fig. 4 shows a schematic of the CARS equipment in the test cell. A representation of the framework of the CARS system is shown under the combustor model. The tunnel controls were set to the desired operating conditions. The run signal given to the tunnel also started the CARS data

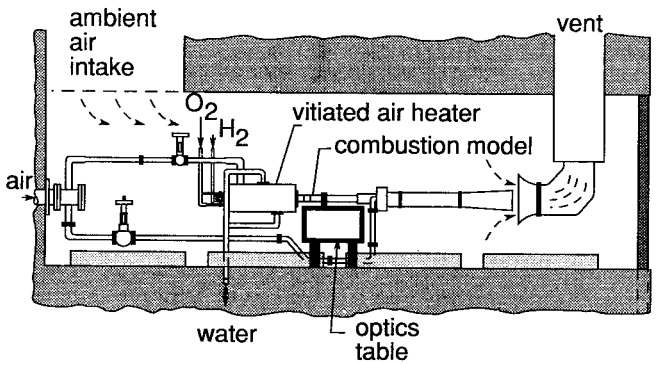

Fig. 4. Schematic of the CARS system installed in the hypersonic propulsion test cell.

acquisition. Run durations were typically 10 to 30 seconds. Turn around time for the tunnel was approximately 15 minutes. During this time, the laser beam alignment was checked to see if adjustments were necessary to maximize signal levels.

RESULTS

Calibrations

To demonstrate the CARS system accuracy, data were collected while sampling one of two calibration devices: the "flat flame burner" or the electrically-heated baffled tube. The results are shown in fig. 5. A straight line is shown to indicate where the data would lie if there were perfect agreement between the CARS data and the calibration device data. The "electrically-heated" data lie below about 1200 K. The data above 1200 K are for "fuel lean" combustion. The standard deviation of the temperature measurements, as shown in fig. 6, illustrates the accuracy of the CARS temperature data. For each point shown, 100 data samples were collected with the CARS system. The maximum deviation is approximately 100 K and occurs at approximately 1400 K. Above this temperature, the CARS spectral data broaden as higher energy levels of the first "hot band" are populated. This spectral broadening provides the basis for a better defined fit of the CARS data to calculated spectra. Thus the standard deviation of the data is observed to decrease above 1400 K. The line fitted to the data is a third order polynomial and is used to emphasize the trend of the data.

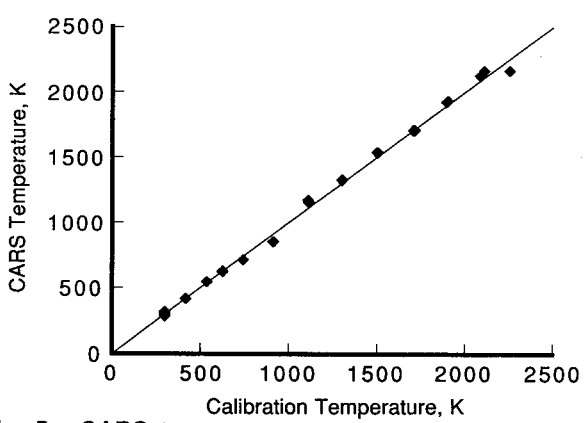

Fig. 5. CARS temperature, measurements compared to calibration data. Perfectly correlated data would lie on the straight line.

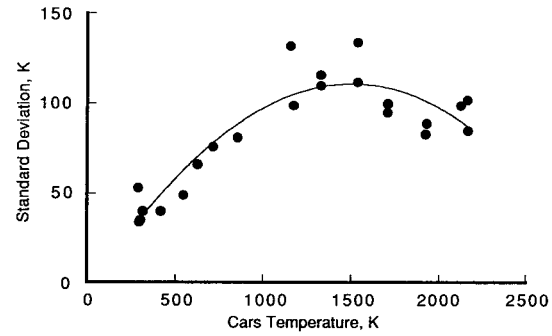

Fig. 6. Standard deviations of the CARS temperature measurements.

Test Cell Data

Fig. 7 shows temperature contour plots at three stations in the supersonic reacting flow of the test cell. The stations were 38.1, 69.5 and 115.9 cm from the exit plane of the nozzle. These contour plots of temperature were collected by moving the CARS measurement volume to collect data at the intersecting points of a 7 X 9 grid in the supersonic reacting flow in the duct. The data indicate a hot, reacting zone beginning at the injection wall and slowly spreading as the flow proceeds downstream. Supersonic reacting flows using this injection scheme have been previously investigated with more traditional techniques (wall pressure and temperature). The CARS data appear as expected in these data plots. The data scatter at selected points in the flow resembles that to be found in both the subsonic and supersonic diffusion burners - that is, it is bimodal in the mixing region as shown in ref. 6. Some data samples were representative of the hot combustion products, others were representative of the incoming vitiated flow.

DISCUSSION

Several issues in the application of CARS to supersonic reacting flow were resolved during the evolutionary laboratory experiments. One of the most important contributions came from fiber optic coupling of the signal to the spectrometer. In the initial experiments, mirrors were used for this coupling. Signal focusing problems arose from this arrangement. Any change in the location of the CARS probing volume resulted in a change in the apparent spatial origin of the CARS signal and a corresponding change in the spatial location of the image at the entrance to the spectrometer. Since the entrance slit was opened to 2 millimeters and rotated to the horizontal position to accommodate multiple images for dynamic range enhancement, the slit characteristics were determined by the quality of the focused images. Thus, a data set always included an air sample to make sure that the library slit function was correct. The use of fiber optic coupling fixed the image in the entrance slit and, once the appropriate slit convolution was determined for the optical arrangement, no new libraries were needed. Another issue was the potential for beam steering when the CARS beams encountered shocks or turbulence. Research with the supersonic diffusion burner, with the static pressure close to atmospheric pressure, showed that shocks caused no discernable beam steering difficulties. Some difficulty had been expected, but the low density changes and the relatively clean flow of the hydrogen-air combustion proved to be a rather benign environment.

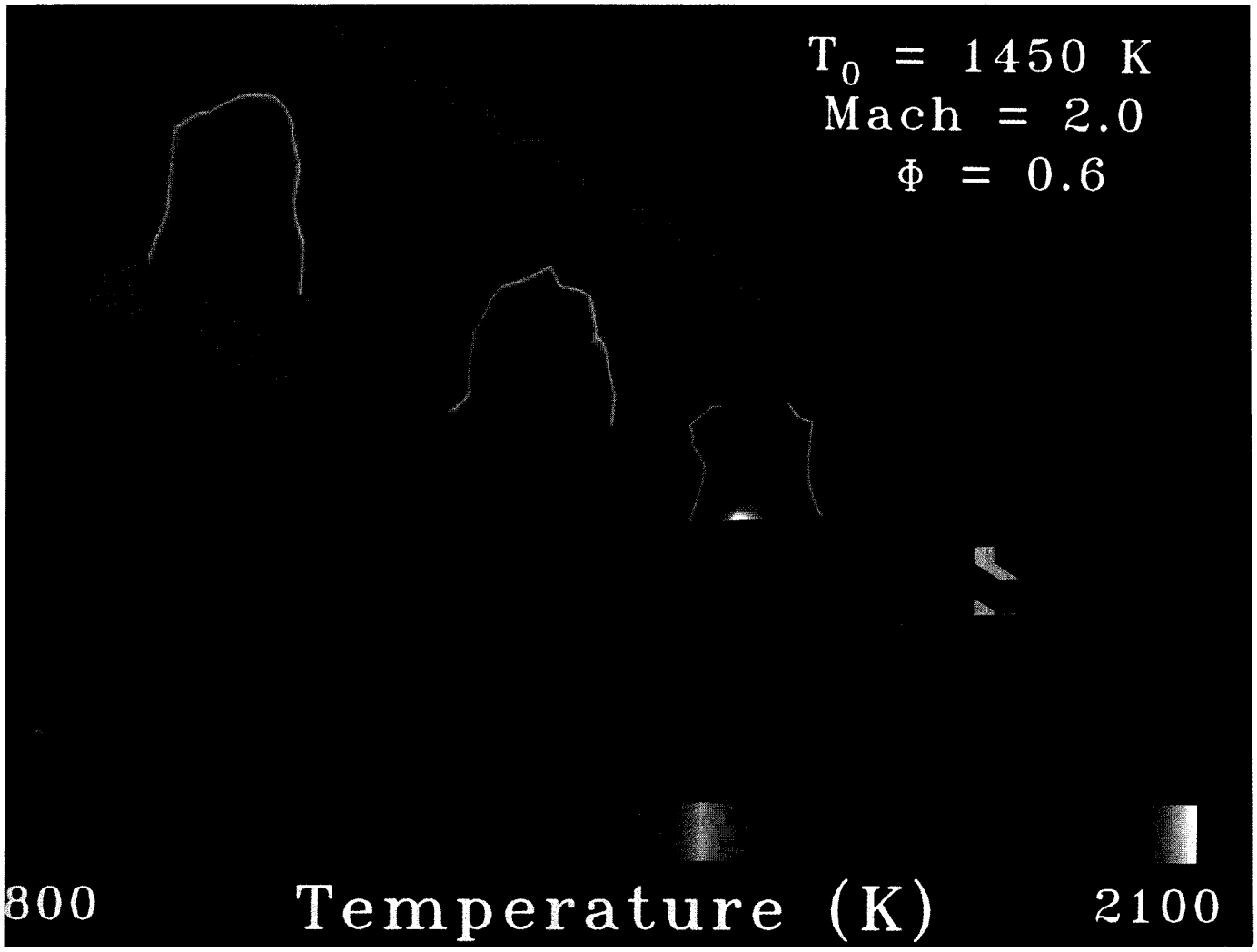

Fig. 7. Temperature contours in representative positions on a cutaway of the duct containing Mach = 2 vitiated flow at its entrance. The data stated in the figure give the total temperature, Mach number, and fuel equivalence ratio of the injected fuel to the air flow.

Obviously, the addition of remote optical tuning and remotely operated flags (either calibration filters or beam blocking flags) was important to the success of the test cell measurements. The rotating wedges were more sensitive tuning devices than mechanisms using traditional manual adjustments.

During investigations with the calibration burner, it became apparent that the only usable results came from the operating range of $0.5<\Phi<1.0$ where Φ is the fuel equivalence ratio. One potentially important result of this limitation on the calibration burner's verification of the CARS library approach is that fuel rich operation is somewhat uncertain. It appears that the equilibrium chemistry which is assumed in the model of Gordon and McBride may not be valid for the fuel rich case. The difficulty with the very fuel lean operating conditions was closely related to the total flow for the burner. Typically, a fixed air flow of 100 l/min was chosen and the hydrogen flow was varied to change the temperature. At such high flow, the flame front becomes detached from the porous plug surface at low Φ values and (determined by other diagnostic techniques) is unstable - that is, it jumps up and down in the lower flame region. Lowering the total gas flow and therefore the velocity at the porous plug surface might yield better results.

The primary source of scatter in the CARS temperature is linked to the noise in the dye laser. Ideally, the dye laser should be a broadband source of constant intensity everywhere in the region of interaction with the species of interest. In reality, small shot-to-shot spectral intensity variations may be seen when observing the spectrally resolved output of the dye laser. These variations cause distortions in the shape of the spectrally resolved CARS signal and consequent scatter in the resulting temperature values.

A potential CARS systematic limitation arose during the small-scale laboratory investigations. One justification for the measurements was to provide sets of data for subsonic and supersonic reacting flow for comparison with computational fluid dynamic calculations. These calculations are typically values at a point in the computational grid. The CARS measurements are collected in an elongated volume; the intersection of three or more focused laser beams. While the interaction length is approximately a millimeter, some contributions may arise from a volume as much as three millimeters in length. In the small-scale regions with high gradients such as in the subsonic and supersonic diffusion burners, the elongated CARS probe volume may not yield results valid for comparison to the point values from CFD results.

As always, signal-to-noise is an issue. If the signal strength is inadequate for processing, information will be lost. Since the CARS data is statistical in nature, most of the samples must provide usable data. Otherwise the data may be biased to conditions which provide a strong (usable) signal. If the signal is strong due to mixing which provides enough nitrogen for a processable signal, the data may be biased to a value other than the true average for the sample. Thus, the test cell measurements were conducted with the CARS system configured to generate a strong resonant CARS signal in nitrogen. This was done by only probing one species and not attempting density measurements.

CONCLUSIONS

Success was achieved in constructing an apparatus to make CARS temperature measurements in the hostile environment of a combustion-heated hypersonic propulsion test cell. Comparisons of the CARS temperature measurements with measuerments of gas temperature in combustion or electrically-heated devices showed good agreement. Standard deviations of temperature measurements in nonturbulent calibration devices showed a maximum value of about 100 K. Such comparisons validated the selected CARS data reduction scheme. Laboratory investigations of subsonic and supersonic diffusion flames were important steps in preparation for the test cell measurements. This first entry with the CARS system into the test cell was largely a proof-of-concept exercise. Some of the system features which were thought to be necessary for the system were not needed. For instance, air supports to avoid structurally transmitted vibrations proved unnecessary.

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