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CARS TEMPERATURE MEASUREMENTS IN A HYPERSONIC PROPULSION TEST FACILITY

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ABSTRACT

Nonintrusive diagnostic measurements have been performed in the supersonic reacting flow of the Hypersonic Propulsion Test Cell 2 at the National Aeronautics and Space Administration's (NASA) Langley Research Center (LaRC). A coherent anti-Stokes Raman spectroscopy (CARS) system was assembled specifically for the Test Cell environment. System design considerations were: (1) Test Cell noise and vibration, (2) contamination from flow field or atmospheric-borne dust, (3) unwanted laser or electrically induced combustion (inside or outside the duct), (4) efficient signal collection, (5) signal splitting to span the wide dynamic range present throughout the flow field, (6) movement of the sampling volume in the flow, and (7) modification of the scramjet model duct to permit optical access to the reacting flow with the CARS system.

The flow in the duct was a nominal Mach 2 flow with static pressure near one atmosphere. A single perpendicular injector introduced hydrogen into the flow behind a rearward facing step. CARS data was obtained in three planes downstream of the injector region. At least 20 CARS data points were collected at each of the regularly spaced sampling locations in each data plane. Contour plots of scramjet combustor static temperature in a reacting flow region are presented for three stations.

INTRODUCTION

Instrumentation for the propulsion facilities at NASA LaRC has been largely dependent upon traditional wind tunnel techniques, e.g., pressure at a surface, thermocouple-based temperature measurements, force measurements, and shock positions from schlieren techniques. This paper describes the first measurements conducted in Test Cell 2 using a CARS system to measure temperature in a reacting supersonic flow. CARS is a laser-based technique which generates signals related to the temperature and density of selected gases in the common probe volume of the system's laser beams. It can make measurements of dominant species from signals generated by a single 10 ns laser pulse. In this series of measurements, the CARS system was configured to measure static temperature with nitrogen as the thermometry species in hydrogen-vitiated air combustion. Measurements with a CARS system have been under way at NASA LaRC since 1981[1,2,3]. The current tests were conducted as a joint effort between NASA LaRC and Los Alamos National Laboratory. The tests included both Laser-induced fluorescence (LIF) and CARS measurements, but only the CARS system and results will be discussed here.

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HARDWARE DESCRIPTION

TEST CELL

An overall view of the Test Cell is shown in Figure 1. A more complete description may be found elsewhere[4]. Gas supplies were located near the facility. Trailer-mounted high pressure >13790 kPa (2000 psi) storage bottles for hydrogen, oxygen, and nitrogen (for purging) provided the test gases. Air was supplied by the central facility which initially compressed the air to 5000 psi and dried it (an important consideration in the humid Tidewater Virginia area). The control room for the facility operations is over the Test Cell area.

The high enthalpy test gas required to simulate scramjet combustor flows was produced by a hydrogen-air combustion heater with oxygen replenishment. Flow rates of the air, hydrogen, and oxygen were set to achieve the desired test conditions. Typical test conditions are listed in Table I.

Table I. Nominal Test Cell gas flow rates. 3% fluctuations in day-to-day operations. 0.58 Fuel equivalence ratio.

air	1.25	kg/s	2.75	lbm/s
hydrogen	0.025	kg/s	0.055	lbm/s
oxygen	0.295	kg/s	0.65	lbm/s
hydrogen fuel	0.0281	kg/s	0.062	lbm/s

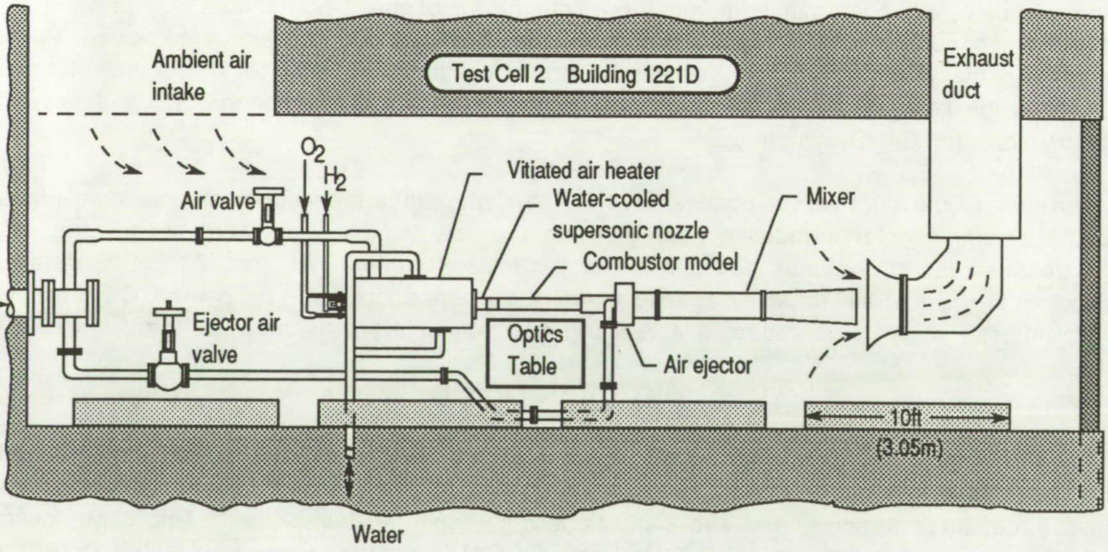

Figure 1. Schematic of hypersonic propulsion Test Cell 2. The CARS equipment was situated under the combustor model with optics supports rising on both sides.

The desired total heater flow rate was a nominal value of 1.58 kg/sec (3.5 lbm/sec). Total temperature and pressure were respectively 1416 K (2550 R) and 827 kPa (120 psia). These conditions yielded a nominal static pressure of 103.4 kPa (15 psia), temperature of 850 K (1530 R), and a unit Reynolds number of 1.22 X 10^6/m (4 X 10^6/ft) after expansion through the water-cooled Mach 2 nozzle. Volumetric oxygen content for the test gas was maintained at 21 percent. An air ejector was connected to the exit of the diverging combustor duct (combustor model in Figure 1) to prevent atmospheric back pressure from influencing combustor performance. Ejector flow rate was set to maintain the static pressure at the end of the combustor near 13.8-20.7 kPa (2-3 psia) for the facility operating with no fuel injection. All flow rates in the tests were measured using ASME sharp edged orifice plates. A programmable controller was used to start fuel injection and the Test Cell and CARS data acquisition systems.

The vitiated air exited the heater through a convergent-divergent two dimensional nozzle achieving nominal Mach 2 at the nozzle exit. A 0.14 m (5.5 inch) straight-sided section followed the nozzle. A rearward facing step of 0.762 cm (0.3 in) height was centrally located in the top of the section. A single 0.61 cm (0.24 in) hydrogen injection port was located in the top of the duct 7.47 cm (2.94 in) behind the injector. Following the step section, the top wall of the duct diverged with a three degree angle; the bottom wall was horizontal. The side walls were parallel from the nozzle exit to the ejector. The duct was fitted with pressure ports along the top, side and bottom which were part of the standard Test Cell instrumentation. Pressure port data were recorded and used in CARS post data processing to confirm set point operation. Optical access ports for the CARS system were located in the side walls 38.1, 69.5 and 115.9 cm (15, 27.5 and 45.625 in) from the nozzle exit. The optical access ports are shown schematically in Figure 2. They provided vertical slits in the side walls for CARS laser beam access. The slits were 3.175 mm (1/8 in) wide and were cut in inserts as shown in the schematic. Thus, blank inserts could be substituted to minimize the influence of shocks from one of the upstream optical ports. As the tunnel flow contained dirty water, provision was made for both purge air and a rotating seal in an effort to maintain clean windows. The rotating seal, a slot cut in a rod, was opened by an air actuator under computer control.

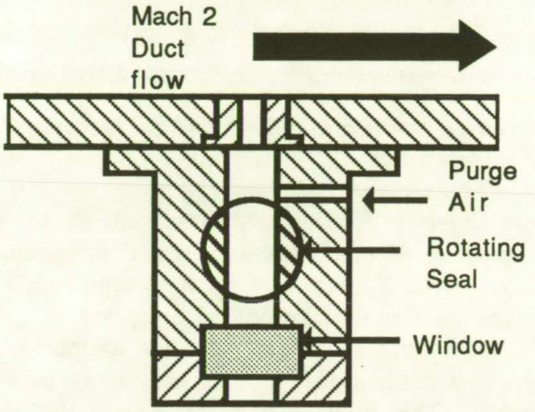

Figure 2. Schematic of the Window assembly.

TEST CELL ENVIRONMENT

Safety considerations were a driving factor in the design of the Test Cell and in detailing its operating procedures. During maintenance, the Test Cell is heated or air conditioned, but during normal operations, the Test Cell is closed and locked and the air ejector draws outside air through roof-mounted louvers to minimize accumulation of combustibles if a leak occurs. No personnel are allowed in the Test Cell while the manifolds are charged; thus, no direct contact with instrumentation is possible for a period beginning about 1/2 hour before a test and during the several hours of a typical set of tests. Sound levels in the Test Cell were known to be in excess of 140 dB. Thus, the CARS apparatus had to be designed to cope with these conditions.

CARS SYSTEM

The CARS system previously used at NASA LaRC has been described elsewhere[2] and will be only briefly detailed here. CARS is a nonlinear Raman process in which laser beams incident on a sample at frequencies ω_1 (pump) and ω_2 (probe) interact through the third-order susceptibility

$$\chi^{(3)} = \frac{2\pi N c^4}{h\omega_2^4}\sum_{v,j}\frac{\Delta_{v,j}(d\sigma/d\Omega)_{v,j}}{\omega_r-(\omega_1-\omega_2)-i\,\Gamma_{v,j}}+\chi_{nr}^{(3)} \qquad (1)$$

of the sample to generate coherent radiation at the difference frequency.

$$\omega_3 = 2\omega_1 - \omega_2 \tag{2}$$

If this difference frequency becomes close to a Raman resonance in the sample, the signal is sharply increased. As this difference is scanned through many resonances, a spectrum is created which can be compared to a calculated spectrum for determination of the temperature of the gas in the sample. In practice, a broadband probe laser is used to generate the complete CARS spectrum in a single 10 ns laser pulse. The intensity of the signal is related to the density, but the system was not configured for density measurements. In equation 1 , N is the number density of the probed species, $\Delta_{v.i}$ is the population difference between the states studied, $d\sigma/d\Omega$ is the Raman cross section and is assumed constant over the frequency range studied, ω_r is the frequency of a Raman active rotation or vibrational state, $\Gamma_{v,j}$ is the Raman half width, and $\chi^{(3)}_{nr}$ is a collection of susceptibility terms which are generally a slowly varying function of frequency.

The general arrangement of the optical components is shown in Figure 3. The support structure for the CARS optical components was assembled from lengths of Klinger 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. A framework was constructed around the rail assembly and over the optics pallet to provide support for a housing around the optical assembly. The framework over the optics pallet formed two boxes separated by an open space through which the tunnel duct passed. This housing was force ventilated by service air to keep out dust from the Test Cell air. In addition, any accumulation of combustibles in the box was prevented--an important consideration for the high energy associated with the laser. Initially, sound absorbing material was considered for addition to the panels which formed the housing, but this was found to be unnecessary. Air bag supports were provided to isolate vibrations transmitted through the floor, but these supports were also found to be unnecessary. Additionally, the air bags allowed unwanted horizontal movement of the entire system, and their use was discontinued.

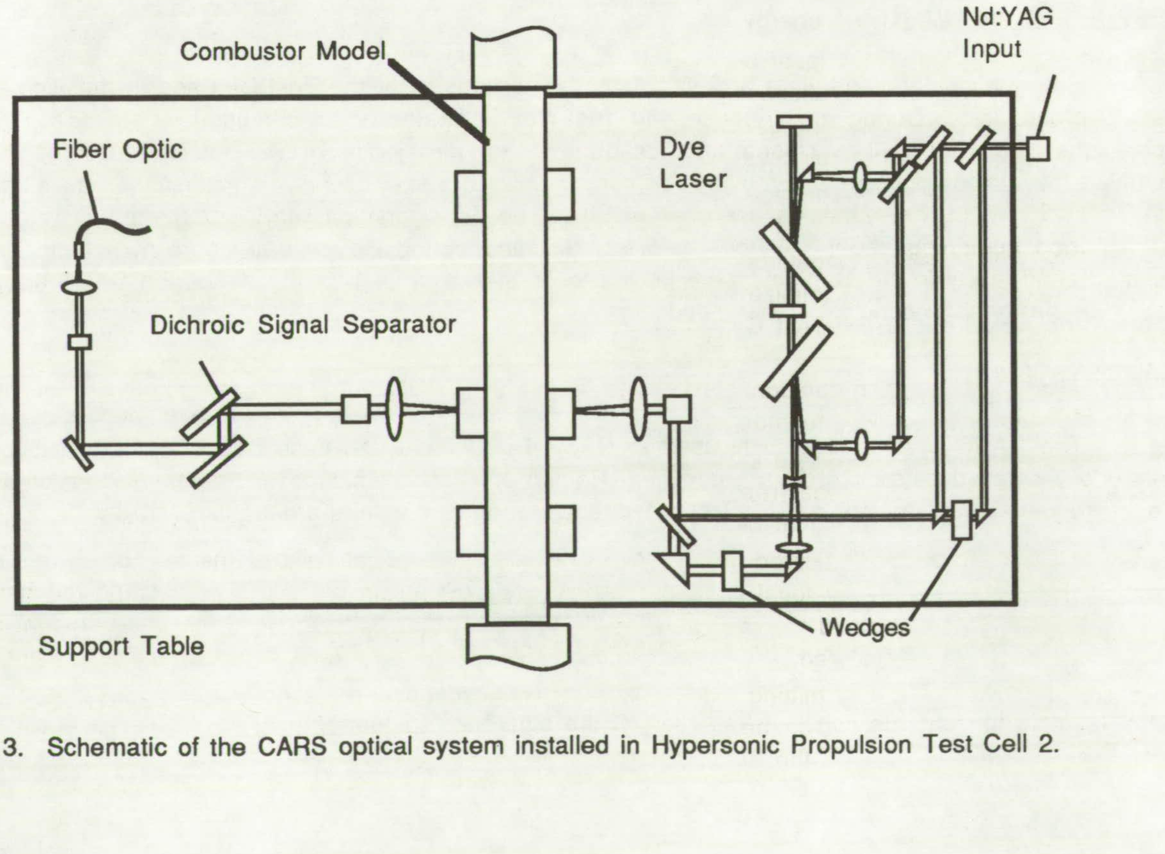

Figure 3. Schematic of the CARS optical system installed in Hypersonic Propulsion Test Cell 2.

The Nd:YAG laser delivered 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 Figure 3, the Nd:YAG laser was split into three parts. One part was used to pump a broadband dye (probe) laser centered about 606.5 nm as required for the CARS system to interrogate nitrogen. The two remaining green (pump) beams were transmitted with the dye laser through a set of prisms to a lens mounted on a translation stage . The components mounted on the translation stages provided movement of the CARS sample volume (the common focal volume of the laser beams) in a plane perpendicular to the supersonic reacting flow. The beams were arranged in the BOXCARS configuration with the beams in a vertical plane. The focusing and recollimating lenses were 28 cm focal length. The interaction length for this arrangement was found to be 0.8 mm (.032 in) full width at half maximum FWHM 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 operator control via the data acquisition computer. 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 pump and probe 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 pump and the probe beam as shown in Figure 3. These wedges were independently rotated by computer controlled stepping motors.

DESCRIPTION OF SYSTEM-TO-MONOCHROMATOR SIGNAL COUPLING

Test Cell 2 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[5] to couple the CARS signal from the Test Cell to the control room where the monochromator and reticon were located. Figure 3 shows some of the details of the hardware used to couple the CARS signal into the fiber. Using the suggestion of S. Fujii[6], a pair of dichroic mirrors were used to separate the ω_1 (pump) laser and ω_2 (probe) energy from the ω_3 (signal) beam. For simplicity the Figure 3, one reflection of the signal and CARS laser beams is indicated on each of the mirrors of the dichroic signal separator; in reality, up to four reflections were arranged on each of the two mirrors. Thus, 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 first surface reflection of the pump beam was calculated to be 10^{-8} of the incident energy (based on ten percent reflection per surface) after propagation through the mirror system. 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 monochromator. Twenty meters of the fiber carried the signal out of the Test Cell to the detector.

Figure 4 shows the components used to couple the CARS signal from the output end of the fiber to the monochromator. At the monochromator, a combination of cylindrical lenses was used to focus the CARS signal into a line image in the entrance slit. It has been shown[7] that a reticon, which was the detector, can demonstrate linear response throughout its operational range by focusing (at the entrance to the monochromator) the signal beam to a line rather than to a point , as would occur if a spherical lens was used. With the indicated combination of lenses[8], the focal point of the horizontal lens was in front of the entrance slit; the focal point of the vertical lens was in the entrance slit and the height of the signal beam was matched to the 2 mm height of the reticon detector; thus, the image height on the detector was similarly matched. As signal intensity varied with density, dynamic range enhancement was provided with a signal splitting device similar to that of Eckbreth[9]; this application differed in that the signal splitter was placed immediately in front of the monochromator with the entrance slit turned horizontally. 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 (16000 counts) was processed. Note that the monochromator slit function was optically determined by the focusing characteristics of the cylindrical lenses rather than by a physical slit.

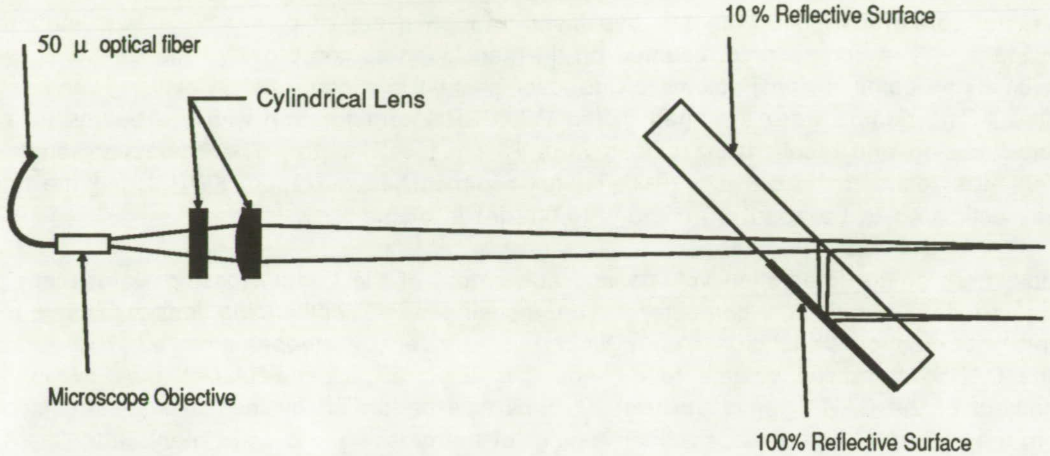

Figure 4. Details of the optics for coupling the CARS signal from the light fiber to the monochromator.

Remote operation of the CARS system required certain beam blocking and attenuation functions be remotely performed. Part of this requirement was established by the necessity to operate the laser continuously to minimize "drift." Switches were devised to allow computer control of two beam blocks, an optical attenuator, and the air activated "seal" on the window (see Figure 2). 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. Thus, the strong CARS signal generated in air could be monitored, as the system was remotely tuned with the rotating wedges. Optical tare values were determined by inserting a beam block in the ω_2 beam and collecting 100 data points. For reacting flow temperature measurements, after the tunnel was started, the window seal was opened, 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.

DATA COLLECTION

CARS data system software was structured to allow computer control of the entire sequence once started. The starting event was produced by manual closure of a relay when the heater combustion was triggered. Both the CARS and Test Cell data acquisition systems were started by this event and both systems started clocks which were recorded with the data sets. About five seconds were required for the heater to reach stable operating conditions, then the injector fuel flow was started. One second was allowed for injector fuel stabilization and the CARS sequence was started. The window seal was opened and all beam blocking and attenuating flags were withdrawn. At this point, data from the next laser firing were transferred to tape (the laser was normally operating even when data were not being collected to provide laser stability). The data system was configured to record intensity measurements from photomultipliers simultaneously with reticon data for density measurements, but density measurements were not attempted. Normally, at least three positions were sampled during one data sequence. This would involve recording twenty shots, stopping data transfer, moving the lens assemblies, and transferring data again. The tunnel operation time was limited by heating of the air-cooled combustion model (duct). At the end of the sequence, the flags were closed, the window seal was closed, and the cycle was reset for the next tunnel start. For each day's operation, the CARS data were collected once with the probe (dye) laser blocked to record optical tare measurements.

Vertical separation for the data points was 0.71 cm (0.28 in), 1.22 cm (0.48 in), and 1.63 cm (0.64 in) at each successive downstream station. Horizontal spacing was 0.95 cm (3/8 in). Thus a 9 X 7 matrix of sampling points was assembled at each of the three stations. The flow was not found to be symmetric; therefore, the survey spanned the duct, limited only by energy density considerations for the windows (some pieces of glass were cracked) and the included angle of the BOXCARS laser beam configuration.

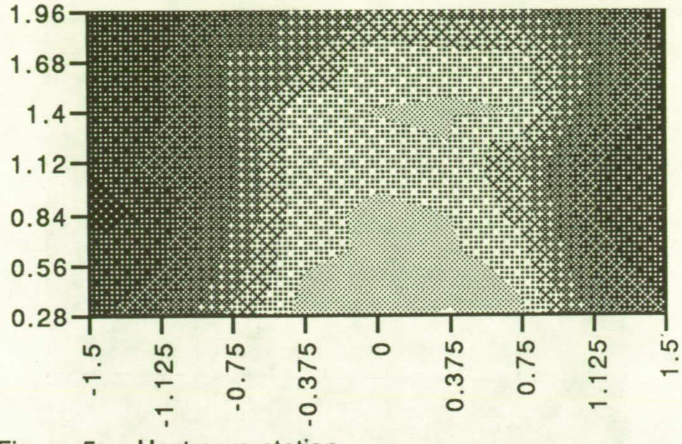

Figure 5a.. Upstream station.

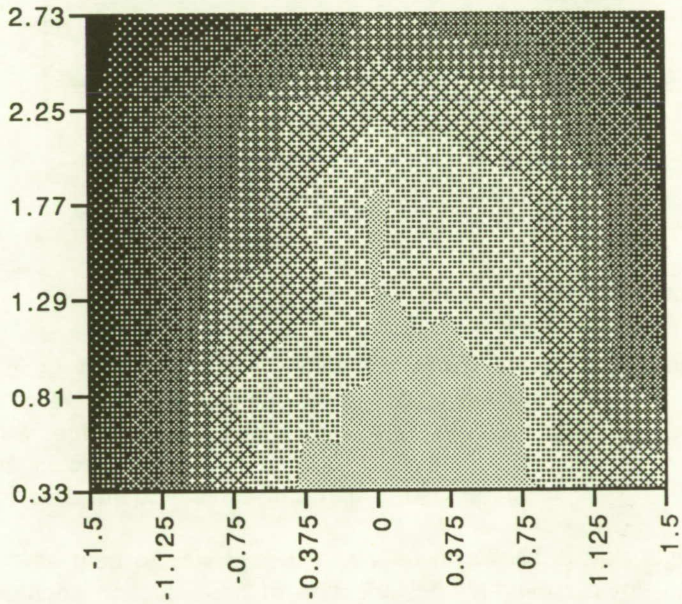

Figure 5b. Middle station

DATA REDUCTION

CARS nitrogen spectra were calculated for 20 degree K temperature increments and stored in a magnetic disc library. The calculations were convoluted with a Lorentzian slit function similar to the technique of Yuratich[10]. The nonresonant background values which were used in the calculations were those of Eckbreth and Hall[11]. The temperature dependence for the calculations was derived from the exponential gap model of Rahn[12]. A least mean squares fit of the CARS-reticon data to the pre-calculated library provided temperatures for the CARS data. A fitting operation for a single point typically took less than a second. Temperature values were recorded in a disc file along with other housekeeping data (run number and elapsed time) for later correlation with tunnel operating data. Library verification was performed by comparing flat flame data collected with the system and processed with the library as described in reference 1.

In post processing of the temperature data, CARS temperatures were identified from portions of the tunnel run which were sufficiently close to the desired operating condition. From these identified data, three matrices of position and average temperature values were assembled. Contour plots of these matrices are presented in Figure 5.

RESULTS AND DISCUSSION

Figure 5 shows contour plots of the CARS measurements of static temperature in a Mach 2 reacting vitiated air-hydrogen flow in a duct. For plotting convenience, the vertical scale has been inverted to appear as if the hydrogen was injected through the bottom wall; it was injected through a perpendicular port behind a backward-facing step on the duct's top wall. Averages of CARS measure-

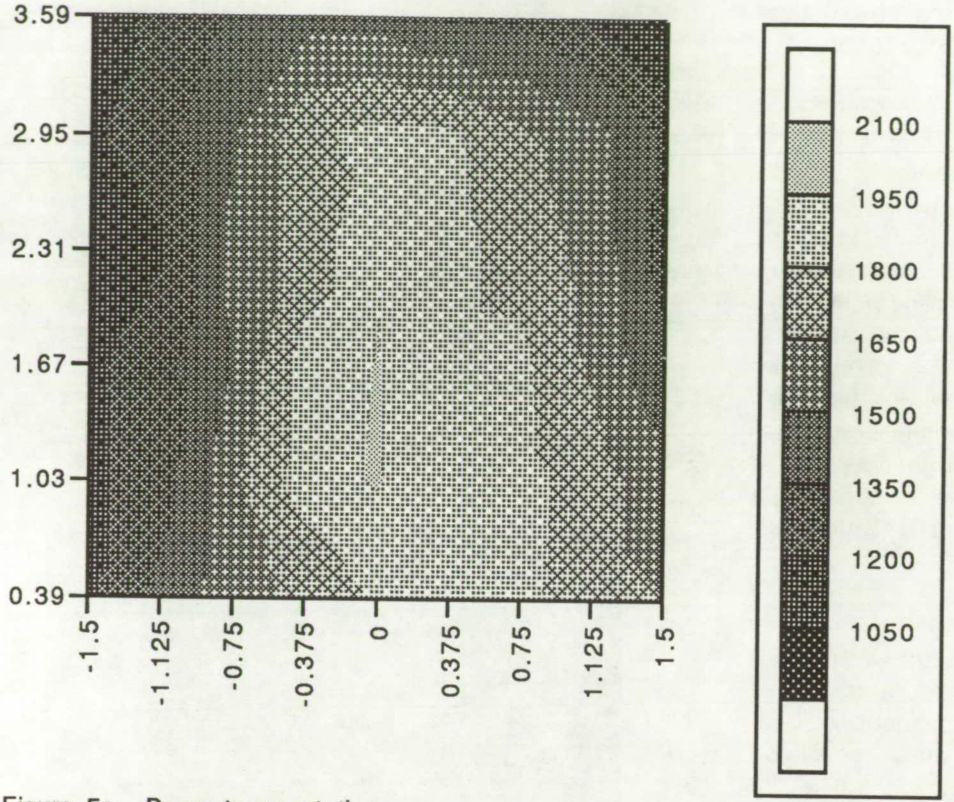

Figure 5c. Downstream station.

Figure 5. Contour plots of CARS measurements of static temperature at three stations in a duct containing a Mach 2 reacting (hydrogen-vitiated air) flow. In these views, the hydrogen fuel was introduced into the flow by an injector behind a rearward-facing step at the bottom of the Figure. Horizontal and vertical coordinates are in inches.

ments were constructed from portions of the data when the tunnel was operating near the flow values specified in Table I. Typically, at least 20 values (2 seconds worth of CARS samples) were averaged and many points include up to 60 samples. Temperature limitations on the uncooled model curtailed CARS data collection to three positions per tunnel operation.

The distribution of static temperature in the duct appears much as expected. The high temperature region at the wall in the upstream station agrees with the observed increase in wall temperature downstream of the fuel injector. Also, injection from a single port is shown to be an inefficient way to heat all the air in the duct since uniformly heated flow was not achieved. The selection of this injection configuration was made with the knowledge that it was a less-than-perfect scheme, but it is a simple technique which has been extensively studied in other tests. Thus, the additions of CARS measurements to the data base will be valuable for comparison with CFD results.

This first attempt at measuring the static temperature distribution in the Mach 2 flow was successful in many regards and, at the same time, indicated several desirable hardware changes. Acoustically induced vibration was not a problem for the instrument. Neither vibration-isolation mounts nor acoustically damping materials to line the inside of the instrument housing proved to be necessary. The high mass of the optical assembly was probably a primary factor in this regard. Likewise, no dust-induced problems arose, and the system design features were adequate to avoid laser-induced ignition when reasonable procedures were used. Thermally induced alignment drift did occur, but the remotely controlled wedges were effective in maintaining correct alignment. Efficient signal coupling from the optical table to the monochromator was achieved and adequate dynamic range was demonstrated for tunnel operating conditions.

Some of the desired changes will make data acquisition easier. Better control of the tunnel flow rates will produce a greater percentage of acceptable data. The CARS system is currently being modified to operate at 30 Hz and the software will be rewritten to shorten the amount of lost time as the

CARS interaction volume is moved from point to point. Provision is also being made to include multi-species density measurements in the system.

SUMMARY

A CARS system has been assembled to perform a survey of static temperature in a reacting vitiated air-hydrogen Mach 2 flow in a duct in Test Cell 2 at NASA LaRC. Measurements were made in three planes perpendicular to the flow. Contour plots of the data are presented.

Several features were included in the system to cope with the adverse conditions found in the Test Cell environment. The system was designed to minimize effects of high noise levels, dust, and thermally induced optical misalignment; to eliminate the potential for system-induced explosion; and to provide for movement of the CARS sampling volume and efficient signal coupling from the CARS system to the detector package outside the Test Cell. Provision was also made for flags and neutral density filters to block or attenuate the beams. All system functions had to be performed remotely as the Test Cell was closed due to safety considerations during normal operations. Provision was made for optical access to the enclosed supersonic flow at three locations.

As expected, the CARS measurements revealed such features in the flow as maximum temperature near the model wall in the region of the injector footprint. Incomplete mixing of the fuel with all of the flow was also shown. These results are consistent with the knowledge that a single perpendicular is not the best injector scheme for the subject flow.

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