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NONINTRUSIVE SPECTROSCOPIC TECHNIQUES FOR SUPERSONIC/HYPERSONIC AERODYNAMICS AND COMBUSTION DIAGNOSTICS

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Abstract

This paper presents an overview of the primary nonintrusive diagnostic techniques being developed by the NASA Langley Research Center to address the validation needs of Computational Fluid Dynamic (CFD) codes. The techniques include absorption in the UV and IR, Laser Induced Fluorescence, electron beam fluorescence, and a number of scattering techniques including Rayleigh, spontaneous Raman, and several coherent Raman spectroscopies. Most of the techniques are highly specialized, require complex data interpretation, and can satisfy only a few of the CFD needs. For these reasons, the evolving trend in flowfield diagnostics appears to favor a mode in which the diagnostic researcher, the experimental aerodynamicist, and the CFD community jointly define experiments based on the aeronautical requirements and on available diagnostic techniques.

1. Introduction

Hypersonic Research in the United States has been brought to a focus during the past few years in response to the particular needs of the nation's National Aerospace Plane (NASP) project. Many new technologies must be developed before the first flight of the NASP X-30, the first research aircraft designed to take off from a runway and attain orbital cruise altitude and velocity using air-breathing scramjet technology. One of these technologies requires new knowledge on the fluid dynamic and thermodynamic state of the supersonic/hypersonic flowfield about the vehicle and throughout the propulsion system. The bulk of this new knowledge will be gained through ground facility testing over a wide range of Mach number and Reynolds number. The results of this testing will be used to validate CFD codes in order to develop confidence in the final aircraft design. This paper presents an overview of the primary nonintrusive diagnostic techniques being developed by the NASA Langley Research Center to address these needs.

2. Nonintrusive Diagnostic Techniques

Table 1 outlines the techniques that will be discussed. Laser spectroscopy is dominant on the list, but other nonlaser techniques are also included which offer unique capabilities and possibilities for flight applications.

2.1 Microwave Discharge

The first two techniques are based on absorption and are line-of-sight averaged measurements over the path length, L. The first uses a microwave discharge lamp to dissociate H_2O and thus generate a low pressure electrodeless discharge containing emission from the OH radical. The emission at 310 nm is used as a background light source in order to measure the absorptivity of OH in combustors. The combustors typically operate at higher pressure (and temperature) than the discharge lamp source. The difference in line widths brought about by this difference in pressure (and temperature) ensures that the peak absorption coefficients in the combustor OH spectrum are sampled for each individual line. High resolution measurements of the absorption for each line could, in principle, be used to generate a molecular Boltzmann plot for the population distribution in the ground state and hence determine the temperature. However, in order to simplify the spectral resolution requirements, measurements are made with a low resolution spectrometer in only 8 spectral "windows" in which the absorption of a number of lines are sampled simultaneously. The system is initially characterized by measuring the spectral output of the background lamp using a high resolution monochromator and by determining the spectral shape of each "window." This information, in conjunction with a library of theoretical absorptivity values, allows one to ascertain the product [OH]·L and the temperature of the OH by "fitting" the theoretical predictions to the measurements.(1) The spectral "windows" are determined by an array of fiber optic bundles placed in the exit plane of the spectrometer. Each fiber optic output is then fed to a separate PMT. Additionally, the light directed to and from the combustor under study is carried on long fibers (10–20 m), thus enabling the instrumentation to be located far from hazardous environments.

An extension of this technique is being developed to allow measurements to be made simultaneously at ten different locations. In this variant, shown in Fig. 1, the light from the background lamp is simultaneously fed to 10 separate fibers and each is chopped at a specific frequency. After each fiber optic is directed to/from the combustor, the outputs of the 10 receiver fibers are simultaneously incident on the entrance slit of the spectrometer. In this manner, the output of the spectrometer carries information from the 10 spatial positions in each of the 8 spectral "windows." The spatial information contained in the signal from each spectral "window" can be separated using FFT techniques. The technique described above can also be applied to NO in an analogous manner using the NO band systems near 227 nm.

2.2 Tunable Diode Laser

The second absorption technique operates in the near IR and employs a tunable diode laser (TDL) as a background light source.(2) This technique is based on the absorption of the O_2 atmospheric band system in the 760 to 780 nm range. Inexpensive, commercially available, GaAlAs diode lasers are employed in a frequency modulated (FM) mode to detect the weak absorption from these magnetic dipole transitions. In this particular application, the TDL is spectrally scanned over several transitions in order to measure temperature and density. The technique will also be used to measure velocity along the laser direction by measuring the Doppler shift.

Table 1. Nonintrusive Diagnostic Techniques

Principle	Technique	Parameters	Configuration	Advantages/ (Constraints)
Absorption	Microwave discharge	[OH],[NO] T_r	Line of sight	Multi-channel Compact, rugged Fiber optic compatible Flight possibilities
	Tunable diode laser	$[O_2]$,$[H_2O]$ T_r,V	Line of sight	Multi-channel Compact, rugged Fiber optic compatible Flight possibilities
Scattering	Rayleigh	ρ	Line, plane	Strong signal (Clustering) (Background scattering)
	Spontaneous Raman	$[N_2]$,$[O_2]$,$[H_2O]$, $[CO_2]$,$[H_2]$,T_r,T_v	Point	Species specific (Weak signal)
	CARS	$[N_2]$,$[O_2]$, $[H_2O]$,T_r,T_v	Point	Species specific Strong signal
	RDV	P,T_t,V T_r,T_v	Point	Species specific No seeding (V) (Scanning system)
Fluorescence	LIF,PLIF, LIPF	$[O_2]$,[OH],[NO], $[H_2]$,$[H_2O]$,T_r	Line, plane	Species specific (Quenching)
	Electron beam	$[N_2]$,$[H_e]$, T_r,T_v	Line	Visualization (Quenching) Flight possibilities

T_t	Translational temperature
T_v	Vibrational temperature
T_r	Rotational temperature
V	Velocity
ρ	Density
[ ]	Species concentration

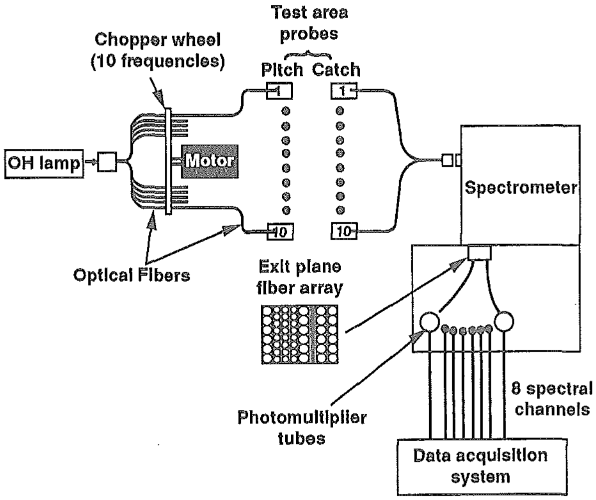

Figure 1. Schematic diagram of the ten position OH absorption system.

The instrument has been designed with a single TDL which is optically split into 8 beams. Eight fiber optic transfer systems and detectors complete the optical train in order to achieve a simultaneous multiple measurement capability. The near IR technique can also be employed to monitor other gases, such as H_2O, in an analogous manner.

2.3 Rayleigh Scattering

Several scattering techniques are being applied today that take advantage of the laser characteristics of narrow linewidth, high power and, in some cases, tunability. The first of these is Rayleigh scattering, in which the large Rayleigh cross-section generates strong signals, particularly in the UV, which can be related to total density. The strength of Rayleigh signals has allowed measurements to be made in a plane in many cases. One problem with Rayleigh scattering is the difficulty of rejecting background scattering (walls, windows, etc.) since the molecular scattering is at the same frequency as the incident light. This is particularly true in a full-size wind tunnel where it is difficult to properly control and baffle the optical train. Another difficulty with interpreting Rayleigh signals relates to the clustering of molecules brought about by the expansion (cooling) necessary to generate supersonic/hypersonic flows. Heating of the flow is routinely performed to prevent liquefaction of the air. Recent studies, however,(3) at Mach 6 show that under typical facility stagnation conditions, clustering of an unknown nature is still present at a level which completely overwhelms the molecular Rayleigh signal, making quantitative interpretation impossible. In situ, free stream measurements of the moisture content revealed a water concentration of <10 ppmv. At this level, water condensation by itself is not capable of producing the observed "Rayleigh" signals. The water and the other constituents of air, such as CO_2, may, however, provide the condensation nuclei by which sizable clusters could be formed. This effect is still under investigation. In spite of the limitations imposed by the clustering, planar Rayleigh measurements are extremely valuable in obtaining visualization of the flow. For example, the mixing of helium into air at Mach 6 was visualized using an excimer laser sheet at 193 nm with an intensified CCD camera.(4) In this experiment, the helium (simulating H_2 fuel) was fed into a Mach 6 air flow through three "fuel" injectors, each 25 mm high by 12.5 mm wide. The laser sheet was situated at several downstream locations and viewed by a UV intensified CCD camera (Fig. 2). Visualization of the mixing was made possible by the low Rayleigh cross section for helium relative to air (lower by a factor of 80). Thus regions containing only helium appear as a dark hole relative to the surrounding air. This effect is further enhanced by the Rayleigh-sized clusters that are present in the air flow. Fig. 3 shows two consecutive (15n sec pulses at 10 Hz) "snapshots" of the Rayleigh image obtained at 10 injector heights downstream from the injectors. These data were obtained for the condition of matched helium and air static pressures. Note the different shapes for the helium "mushroom" as it lifts off the surface and mixes into the air stream. Although not evident in the individual "snapshots", videotape replays appear to show the entrainment of air into the "stem of the mushroom" brought about by vortical motion generated at the injectors.

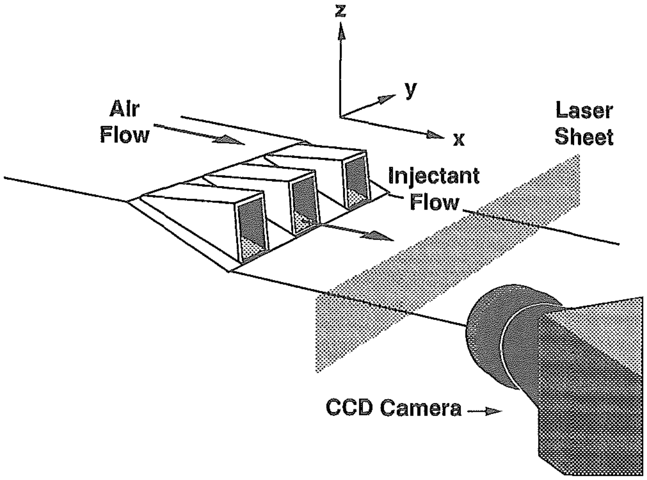

Figure 2. Experimental arrangement of the three injector model in a Mach 6 air flow. The pulsed excimer laser sheet is positioned downstream of the injectors and is viewed by a gated, intensified CCD camera.

Fig. 4 shows the averaged Rayleigh flowfield (22 laser shots) for the central injector and the mean density of air for the same region deduced from probe measurements. Although the clustering in the air prohibits a quantitative comparison, the qualitative agreement between the two is excellent. The individual "snapshots" also provide a qualitative assessment of the fluctuating component (unsteadiness) in the flowfield, something not available from probe data. It should be noted that the temperature distribution in this flowfield (cooler on the periphery of the "mushroom") is expected to have a strong effect on the clustering and could account for some of the enhanced contrast between the helium/air interface.

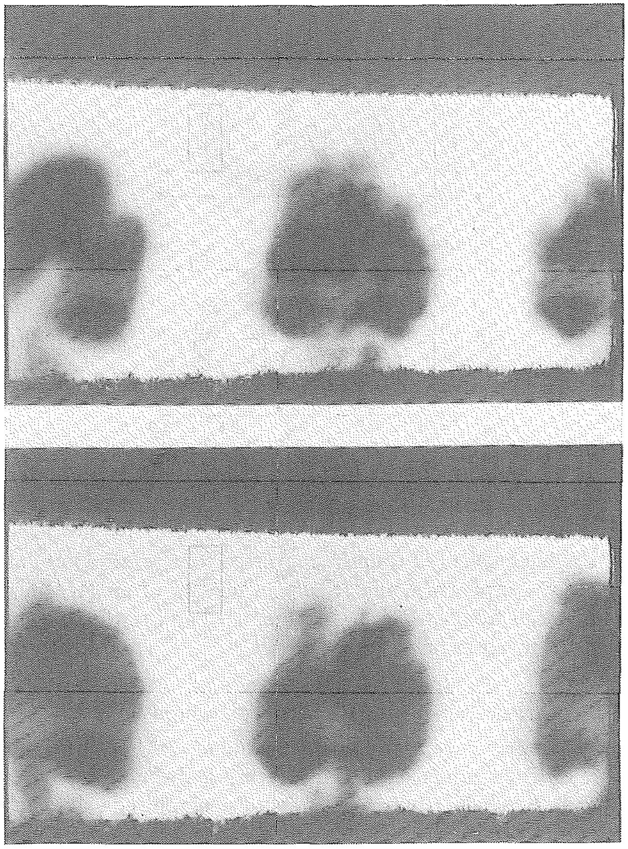

Figure 3. Two consecutive Rayleigh "snapshots" obtained at ten injector heights downstream from the injection plane.

2.4 Spontaneous Raman Scattering

In contrast to Rayleigh scattering, Raman scattering is species specific and occurs away from the incident frequency, making it easier to reject the background. Raman cross-sections, however, are small (typically 0.1–1.0% of Rayleigh values) and the resulting signals are weak. For example, vibrational Raman measurements of N_2 were made in the low density Mach 6 free stream as a way of checking the Rayleigh clustering signal described above.(3) For these experiments, a frequency doubled (532 nm), Nd:YAG laser (60 mJ/pulse @ 10 Hz) was employed as a light source to focus on the tunnel center line with a 40 cm focal-length lens. Practical gathering optics (f/5) focused the scattered light from a 1 cm segment of the laser beam onto a double monochromator outfitted with a PMT. For this situation, signal averaging for 20 sec was required to obtain a reasonable S/N.

The use of a high power (200 mJ/pulse), UV (248 nm) excimer laser to gain a ν^4 advantage in Raman cross-section has been employed to perform diagnostics on a Mach 2 supersonic combustor.(5) The atmospheric densities provided by this combustor, coupled with the opportunity to use fast gathering optics (~f/1) to focus light from a point in the combustor to the slit of a polychromator, allowed single shot measurements of the major species densities (N_2, O_2, H_2 and H_2O) to be made. By translating the combustor, simultaneous density profiles, along with local temperature measurements, provided a unique picture of the turbulent mixing and chemical reactions taking place in a supersonic reacting flow.

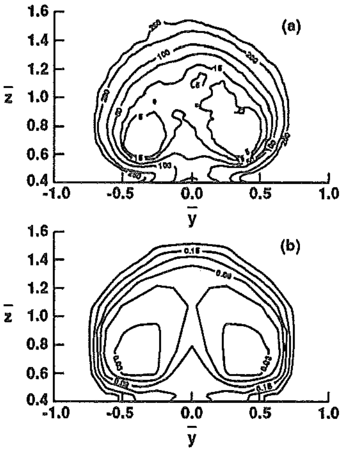

Figure 4. Qualitative comparison of the flowfield downstream of the central injector obtained from (a) averaged Rayleigh data (22 frames) converted to pressure (torr) at room temperature and (b) mean density of air (Kg/m^3) deduced from probe measurements. The coordinates are normalized to one injector height.

2.5 Coherent Anti-Stokes Raman Scattering (CARS)

A popular coherent Raman technique, CARS, has been developed to enhance Raman scattering through nonlinear effects. Typically, two pulsed lasers are employed such that their difference in frequency equals the Raman molecular frequency. The two laser beams are arranged in a crossed-beam (BOXCARS) mode to maximize the spatial resolution and in a spectrally "broadband" mode in order to generate temperature and density information with a single laser pulse. The CARS signal is generated at the intersection of the pump and Stokes beams and carries the diagnostic information on an efficiently controlled "laser-like" beam. The present system has been designed to simultaneously measure N_2 temperature, N_2 number density, and O_2 number density. An extension is under way to add H_2O number density as a measurable. The system has been used extensively to map the Mach 2 Hydrogen/Air combustor described earlier and the results compared favorably to computational fluid dynamics (CFD) codes. More recently, the optics have been "hardened" and the system has been demonstrated in a hostile combustion test cell environment.(6)

2.6 Raman Doppler Velocimeter (RDV)

Another coherent Raman technique is under development that uses either Inverse Raman Spectroscopy (IRS) or Stimulated Raman Gain Spectroscopy (SRGS). In these coherent versions, two focused laser beams (one pulsed and one c.w.) interact simultaneously with the molecules in a quasi-c.w. arrangement. As in CARS, the difference in frequency of the two lasers equals the molecular Raman frequency of the molecule being probed. In this case, however, one of the lasers is scanned in frequency and the narrow laser linewidths allow a measure of the Doppler shift of the individual Raman lines. In this way, the velocity of the molecules themselves is measured (no particle seeding required), circumventing any particle lag problems and also bypassing any difficulties in seeding particles into specific regions of interest. The Doppler shift is actually obtained through the difference in frequency shift between the forward and backward scattered Raman peaks and, in addition, the two line shapes jointly determine the gas translational temperature, T, and pressure, P. In this manner, all three parameters (V,P,T) can be determined from frequency difference measurements independent of intensity or absolute frequency considerations. This technique was initially employed in a concentric IRS mode (Ar^+ probe, tunable pulsed dye amplified pump) and successfully demonstrated that the complex optical configuration would work in a major wind tunnel environment and geometry.(7,8) The system has more recently been reconfigured in the SRGS mode (tunable dye laser probe, Nd:YAG pump) in order to take advantage of the increased energy per pulse available using a narrow-line Single Axial Mode (SAM) Nd:YAG laser. The new configuration also employs crossed-beams to increase the spatial resolution. These improvements complicate the spectral analysis since the line shapes must also be modified to account for Stark broadening brought about as a result of the increased power density in the focal volume.

2.7 Laser Induced Fluorescence (LIF)

Laser Induced Fluorescence (LIF) and Planar Laser Induced Fluorescence (PLIF) techniques have gained in popularity in recent years due to the availability of tunable lasers and the opportunity they afford in increasing the detection sensitivity to specific species.(9) LIF is a two-step process in which the laser photon is first absorbed by a specific line or band, followed by fluorescence which, at low densities, is subsequently emitted with the characteristic lifetime of the upper state. At higher densities, however, collisions with other molecules occur during the lifetime, which alter the internal energy of the system and also quench the fluorescence. Quenching significantly reduces the fluorescence yield and depends collectively on the concentrations of all other species present. Since local, instantaneous information on the absolute species concentrations of all the colliding partners and the local temperature is generally not known, the interpretation of the fluorescence signals is an intractable problem. The most recent technique to circumvent the quenching problem is Laser Induced Predissociation Fluorescence (LIPF) where transitions are selected in which the upper electronic state is crossed by a repulsive state. In this situation, the upper state predissociates at a faster rate than the collision rate with the end result that collisions have little, if any, effect on the fluorescence. The negative side of LIPF is that the signal is reduced drastically since a significant proportion of the excited molecules are dissociated in the process. Nevertheless, the technique is finding widespread use and many molecular states have been identified that exhibit predissociation.(10) One of the major species of interest to aerodynamics is oxygen which is accessible through the Schumann-Runge (B←X) band with an excimer laser operating at 193 nm (ArF) or 248 nm (KrF). This technique is being developed for both cold and hot flows. At the very low temperatures characteristic of hypersonic free streams, the O_2 LIF signals generated using the excimer at 193 nm are marginal due to the fact that only high rotational levels (unpopulated at low temperatures) are accessible over the limited frequency range provided by the gain profile of the excimer. For hot flows, the excitation of high rotational levels is no longer a problem, but many additional O_2 vibrational bands come into play which complicates the spectrum. Spectral interference from other molecules found in hot flows, such as NO, must also be taken into account.

The application of LIF techniques to major aerodynamic facilities today suffers from two major drawbacks: signal intensity and quantification. Many of the LIF techniques demonstrated to date use fast optics and the best lasers available but still exhibit field-of-views that are measured in millimeters or centimeters. The scaling of these techniques to meter-sized facilities severely limits their usefulness. Even where there is adequate signal, most measurements have not been quantified since factors such as the fluorescence yield are very difficult to determine.(9) Nevertheless, the species specific flow visualization attained by LIF techniques has been extremely valuable, particularly in supersonic combustion diagnostics, where the delineation of flowfield structure, reaction zones, and shock waves have helped to characterize turbulent flames. At Langley, PLIF has been used to examine OH profiles from a Mach 2 combustor. The OH "snapshots" showed flow patterns which were "frozen" by the 15n sec pulse length of an excimer laser operating at 308 nm (XeCl). The qualitative image data showed changes in the structure of the reacting jet and illustrated the localized OH concentrations occurring on a pulse-to-pulse basis.

2.8 Electron Beam Fluorescence

Following the pioneering work by Muntz,(11) considerable work was done at LRC to develop the Electron Beam Fluorescence (EBF) technique in the late 60s and early 70s. In this technique, electron-beam excitation of N_2 generated fluorescence from the N_2^+ ion at 391.4 nm which could be related to the N_2 density. The rotational and vibrational temperatures could also be determined by the spectral distribution. Quenching of the EBF is not a problem for densities below 10^{16} cm^{-3}. Although there is no active EBF program at this time at Langley Research Center, the resurgence of interest in hypersonic flows will most likely trigger a revitalization of this work, particularly as testing approaches the Mach 20 arena and the extremely low densities encountered.

3. Discussion

The requirements for flowfield diagnostic techniques are being driven in part by CFD solutions that are being developed to generate 3-D flowfields for complex aerodynamic shapes. This technology is maturing rapidly but still requires experimental validation. This paper has presented an overview of a number of diagnostic techniques being developed at Langley Research Center to address the validation needs of the CFD community. It would appear that no single technique can satisfy even a few of the CFD requirements, but rather each requirement must be met by a specific instrumental solution based on many factors [ex. model/test section geometry, spatial/temporal resolution, facility run time, and general flowfield characteristics (T,P,V)]. As a result of these specialized applications and the complex data interpretations required, it is questionable whether many will attain the "dedicated" instrument status that has been possible with Laser Doppler Velocimeter (LDV) systems, for example. Rather, the trend appears to favor a research mode of investigation where the diagnostic researcher works hand-in-hand with the experimental aerodynamicist and the CFD community to jointly define the experiment based on the aeronautical requirements and on available diagnostic techniques.

Finally, it should be recognized that many of the evolving diagnostic techniques are not only species specific, but, in addition, measure (and sometimes drive) the internal state distribution of the probed molecules. These measurements, at the molecular level, require a detailed knowledge of the collision physics and reaction dynamics as an integral part of their interpretation. Thus the newer diagnostics represent a revolution of sorts in that they are leading to an understanding of aerodynamic phenomena from the molecular level rather than from the traditional bulk properties approach.

4. References

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