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LASER DIAGNOSTICS FOR SMALL ROCKETS

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SUMMARY

Two nonintrusive flowfield diagnostics based on spectrally-resolved elastic (Rayleigh) and inelastic (Raman) laser light scattering have been developed for obtaining local flowfield measurements in low-thrust gaseous H_2/O_2 rocket engines. The objective is to provide an improved understanding of phenomena occurring in small chemical rockets in order to facilitate the development and validation of advanced computational fluid dynamics (CFD) models for analyzing engine performance. The laser Raman scattering diagnostic has been developed to measure major polyatomic species number densities and rotational temperatures in the high-density flowfield region extending from the injector through the chamber throat. Initial application of the Raman scattering diagnostic has provided O_2 number density and rotational temperature measurements in the exit plane of a low area-ratio nozzle and in the combustion chamber of a two-dimensional, optically-accessible rocket engine. In the low-density nozzle exit plane region where the Raman signal is too weak, a Doppler-resolved laser Rayleigh scattering diagnostic has been developed to obtain axial and radial mean gas velocities, and in certain cases, H_2O translational temperature and number density. The results from these measurements have been compared with theoretical predictions from the RPLUS CFD code for analyzing rocket engine performance. Initial conclusions indicate that a detailed and rigorous modeling of the injector is required in order to make direct comparisons between laser diagnostic measurements and CFD predictions at the local level.

TECHNICAL DISCUSSION

Small, low thrust chemical rockets are currently used in almost all spacecraft auxiliary propulsion systems (APS). Since spacecraft payload and operating lifetime are limited by the amount of propellant carried on-board, optimizing the performance of the APS thrusters is of critical importance. Standardized performance analysis methodologies, while effective for large thrust classes, are generally inadequate for modeling the thick reacting shear and boundary layers present in small, fuel-film cooled rockets. Advanced computational fluid dynamic (CFD) models, such as the RPLUS code[1-3], provide the potential for enhanced rocket engine performance analysis through a more rigorous modeling of the combustor and nozzle flowfields. Localized flowfield data are necessary, however, for both assessing the accuracy of the model, as well as providing an improved phenomenological understanding of the processes occurring inside low thrust chemical rockets. To meet this objective, two diagnostics have been developed based on spectrally-resolved laser Rayleigh and Raman scattering. The Raman scattering diagnostic has been directed toward the measurement of major polyatomic species number densities and rotational temperatures in the higher density regions of the thrust chamber, specifically from the injector and combustor regions through the throat. Due to the relatively weak Raman scattering cross-sections, however, the signal strength in the low density nozzle exit and plume region is generally too low to obtain a sufficient signal-to-noise ratio (SNR). In this region, Doppler-resolved laser Rayleigh scattering has been developed to obtain measurements of axial and radial mean gas velocity and, in certain situations, H_2O translational temperature and number density. Each technique is discussed in more detail in the following sections along with initial results and a comparison with CFD predictions from the RPLUS model.

The Rayleigh and Raman scattering diagnostics were implemented in a low thrust rocket test facility at the NASA Lewis Research Center. The facility was developed to support performance and life testing of gaseous hydrogen/oxygen rocket engines with thrust levels of 22-220 N. Testing was conducted in a low pressure test chamber capable of simulating an altitude of 35 km. The altitude chamber measured 1.82 m in length by 0.91 m in diameter. Three optical access ports were located at 90° relative to the thruster axis with a fourth additional port canted at 60°. A supersonic diffuser with an inlet diameter of 102 mm was used to capture the rocket exhaust and transport it outside of the altitude chamber. A complete description of the test facility is given in Reference 4.

Laser Rayleigh Scattering

The laser Rayleigh scattering diagnostic is described in detail in References 5-8. In rarefied gases, such as those found in the rocket exhausts used in these tests, the Rayleigh scattered spectrum is simply the sum contribution of the scattering from all molecules in the probe volume. Under sufficiently high spectral resolution, the mean gas velocity can be obtained from the net Doppler shift in the profile, the translational temperature from the Doppler width, and the number density from the total scattered power. The measurement of the temperature and number density using Rayleigh scattering is subject to the requirement that the species composition be known, which is generally not the case. For fuel-rich mixtures, however, the scattering is largely dominated by water molecules, thus temperature and density measurements can be obtained with minimal error due to uncertainty in the actual composition. For flowfields with oxidizer-rich regions, temperature and density measurements are subject to greater uncertainty. In these situations, the Rayleigh technique is used primarily as a flowfield velocimeter. The requirement of a known composition does not affect the measurement of the mean gas velocity and thus this represents the most robust aspect of the technique.

Initially, the Rayleigh diagnostic utilized a continuous wave argon ion laser and photon counting signal detection electronics. Due to the weak signal from the low density plumes, the Rayleigh spectrum was readily swamped by combustion generated luminosity emanating from the combustion chamber. This prevented measurements from being obtained at the nozzle exit. In order to reduce the sensitivity of the technique to luminous interferences, the cw argon ion laser and photon counter were replaced with a pulsed, injection-seeded Nd:YAG laser (150 MHz spectral bandwidth) and time-gated signal detection electronics. This allowed measurements to be obtained at the nozzle exit plane, thereby providing a more direct comparison with exit plane predictions from rocket performance models. As the Rayleigh scattered signal was at essentially the same wavelength as the laser, extensive use of apertures, baffles, and light traps was required in order to eliminate interferences from stray scattered laser light within the chamber. A schematic of the pulsed Rayleigh scattering diagnostic is shown in Figure 1.

For each test run, the Fabry-Perot interferometer was used to obtain a reference scan of the unshifted laser line and a scan of the Rayleigh scattered light from the rocket exhaust. A maximum likelihood curve fit procedure was then applied to the reference scan in order to obtain the instrument response function. The same curve fitting procedure was then applied to the hot fire data by convolving the Rayleigh scattering model function with the instrument response function to estimate the net Doppler shift, Doppler width, and total scattered power. Representative examples of the reference and Rayleigh scans, along with their associated curve fits, are shown in Figure 2. By traversing the collection probe along the beam path across the exit plane, a radial profile was obtained. Axial and radial velocity profiles obtained on a Space Station prototype thruster with a 30:1 nozzle exit area ratio are shown in Figure 3, along with the predictions from the RPLUS model. Discrepancies between the measured and predicted profiles are attributed to flow stratification between the hydrogen and oxygen in the core region of the thruster which was not addressed in the model.

Laser Raman Scattering

A complete description of the Raman diagnostics facility is given in References 8-10. The layout of the facility is shown in Figure 4. A flashlamp pumped dye laser, lasing at a nominal wavelength of 595 nm, was delivered via a fiberoptic cable into the altitude chamber and then focused into the plume of a low area ratio rocket nozzle. The Raman scattered signal was then coupled into a second fiberoptic cable and transported out of the altitude chamber for spectral processing. The collected light was focused into a spectrometer containing either a 300 or 1200 groove grating, dependent on the application. For simultaneous multispecies detection, the 300 groove grating provided a spectral resolution which allowed simultaneous detection of oxygen, nitrogen, and water with a single linear array detector. For temperature measurements where high resolution of the line shapes was required, a 1200 groove grating was used instead. A Raman notch filter with 10^6 rejection at the laser wavelength was used to eliminate interferences from spuriously scattered laser light.

An gated-intensified linear diode array was used to measure the Raman scattered signal. With the use of background subtraction, this pulsed system could extract very weak signals from the noise. The measured temperature could be extracted from the measured line shapes using a model function based on Raman theory and the instrument function of the detection equipment. Calibration factors were obtained from a reference gas at known temperature and number density. A maximum likelihood parameter estimation procedure completed the data reduction. The instrument function was measured using a helium neon laser line and a mercury lamp. Oxygen and nitrogen spectra obtained in atmospheric air were used as calibration spectra. Typical nitrogen spectra, both measured and calculated, for two different temperatures are shown in Figure 5. The Raman diagnostic was then applied near the exit of a low area ratio (1.4:1) nozzle where the density was still high enough to generate a measurable signal. The injector and chamber geometry were the same as in the Rayleigh scattering measurements shown in Figure 3, except for the cutoff nozzle. The oxygen number density and rotational temperature profiles from these measurements are shown in Figure 6. As with the Rayleigh results, it is believed that the discrepancies between the measurements and predictions are the result of incomplete mixing and flow stratification in the core flow region between the hydrogen and oxygen. Current efforts are directed toward obtaining Raman measurements inside the combustion chamber through the use of a two-dimensional, optically-accessible rocket engine. Results from these efforts will be presented in Reference 11.

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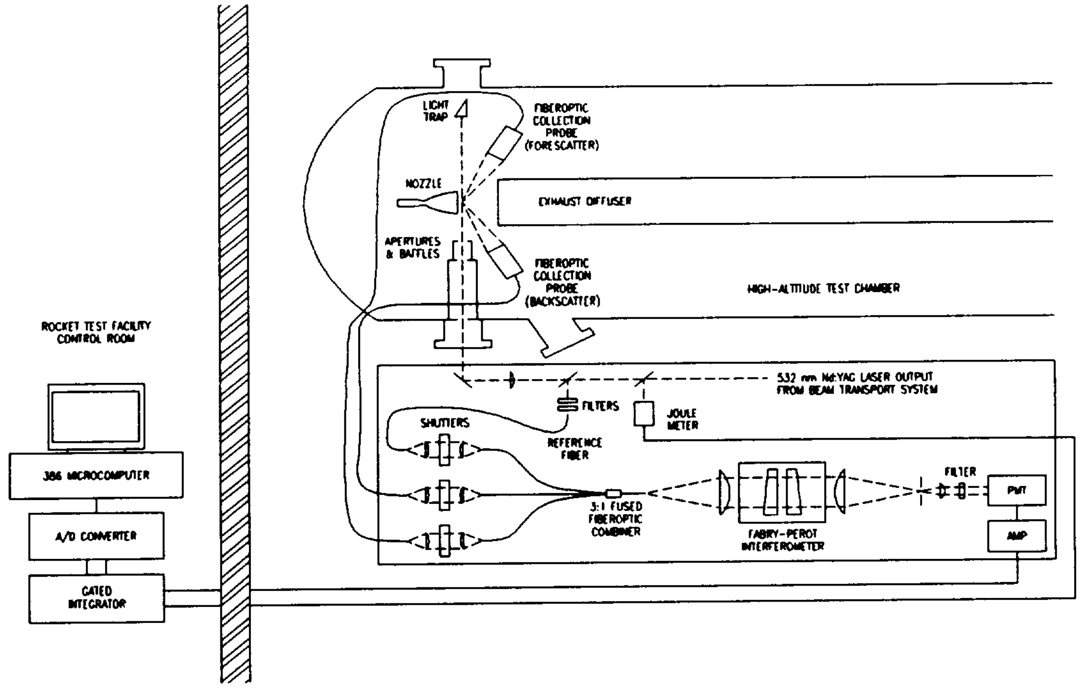

Figure 1. Schematic diagram of overall optical arrangement of pulsed laser Rayleigh scattering diagnostic.

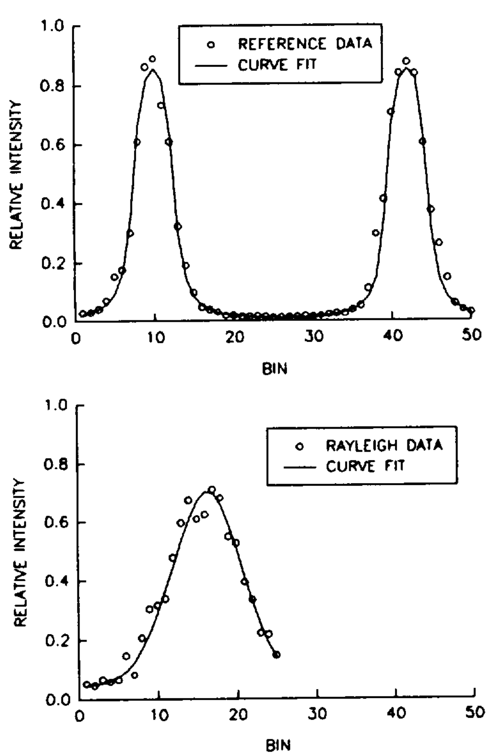

Figure 2. Fabry-Perot scan measurements of unshifted reference laser line (top) and Rayleigh scattering profile in rocket exhaust (bottom).

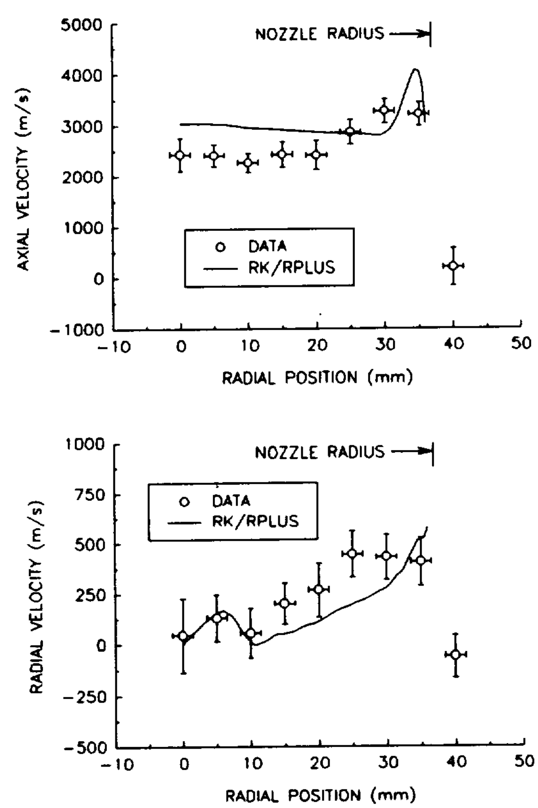

Figure 3. Comparison of measured axial (top) and radial (bottom) velocity profiles with RPLUS predictions.

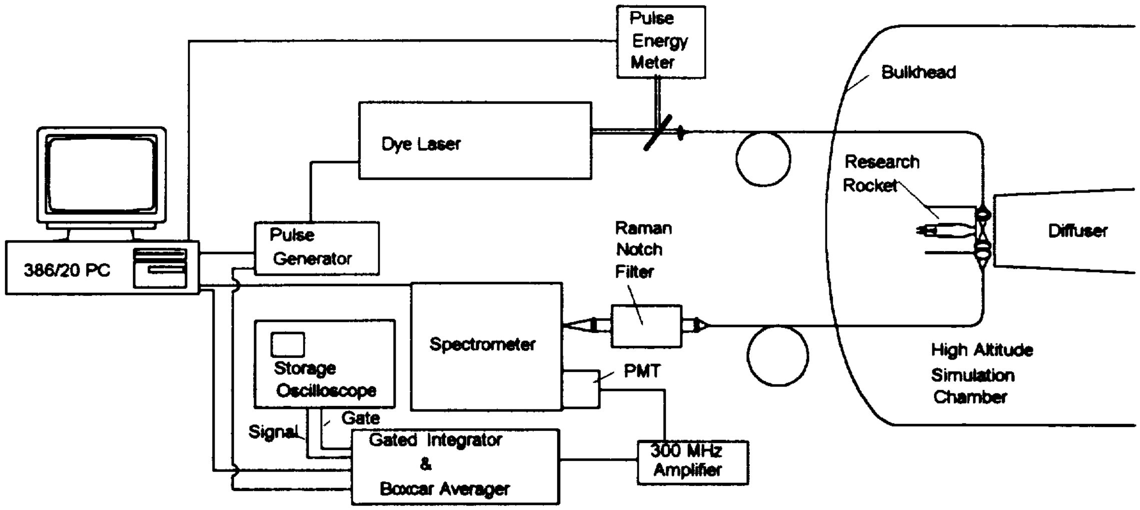

Figure 4. Schematic of Raman scattering diagnostics data acquisition system.

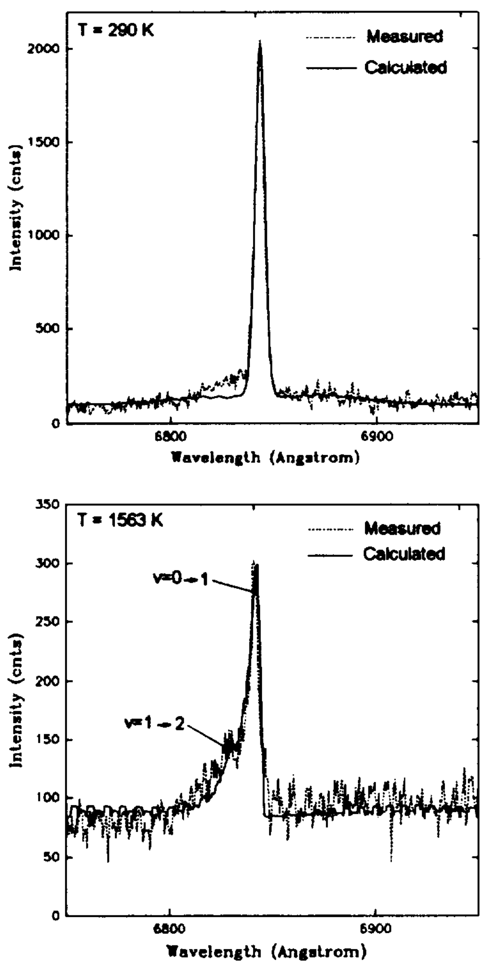

Figure 5. Measured and calculated Raman Q-branch spectra of nitrogen at T=290 K (top) and T=1563 K (bottom).

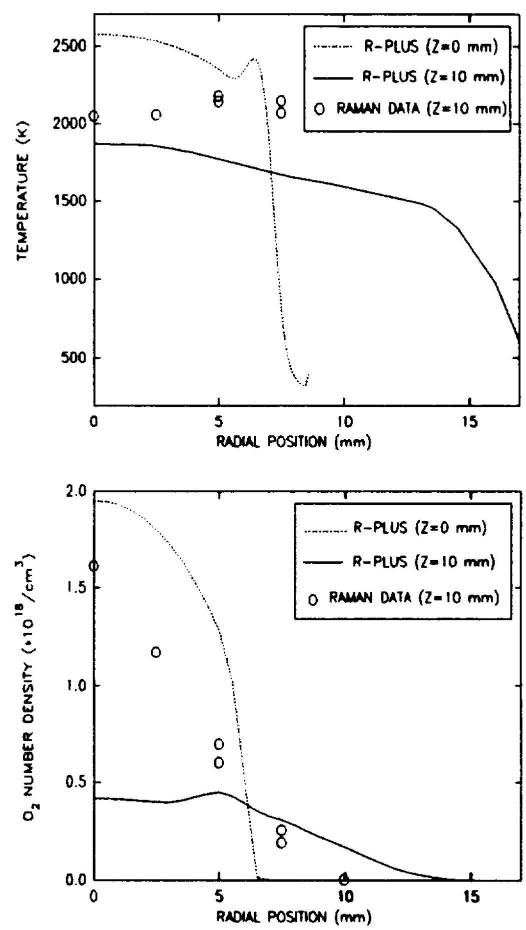

Figure 6. Raman temperature (top) and O_2 number density (bottom) measurements in the exit plane of a low area ratio nozzle.