Hypersonic Flowfield Measurements Using Laser-Raman Spectroscopy

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Theme

THERE is a continuing need for spatially-resolved, nonperturbing measurements of gas temperatures and number density in the high speed flowfields of aerospace ground test facilities. Although the electron beam fluorescence technique[1] satisfies these requirements, its upper density limit of application is on the order of 10^{16} to 10^{17} cc^{-1} as a result of collisional quenching processes. In contrast, the characteristic time of photon-molecule scattering processes is sufficiently small to preclude intermolecular collision effects over the density range normally encountered in aerospace test facilities. Consequently, Raman scattering spectroscopy is not susceptible to high density limitations resulting from intermolecular collisions and, moreover, fulfills the desired, above-mentioned, requirements for a flow diagnostic technique.

Contents

For diatomic and polyatomic molecules the relative intensity distribution of the pure rotational Raman displacements is related to the rotational temperature T_R which, in the absence of rotational relaxation, equals the translational or static gas temperature. Therefore, spectroscopic analysis of the rotational Raman scattering spectrum, which results from the interaction of an intense, monochromatic laser beam with the molecular species, yields T_R of the gas specie.

The pure Stokes rotational Raman line intensity I_J for a linear molecule is given by[2]

$$\ell n\left\{I_J\, T_R\, \lambda_J^4/T_J\left[\frac{(J+1)\,(J+2)}{(2J+3)}\right]\right\} = \ell n\, C_1 - J(J+1)\theta_R/T_R \qquad (1)$$

where J is the rotational quantum number, λ_J is the wavelength of transition of the J^{th} level, θ_R is the characteristic rotational temperature, T_J is the relative detection efficiency, g_J is the nuclear spin degeneracy, and C_1 is a constant. An iterative computer calculation, using Eq.(1) obtains a least squares fit of the measured values of I_J as a function of $J(J+1)$, the slope of which yields T_R. For this calculation the I_J values are weighted by the reciprocal of their statistical variance. Therefore, the more intense and, thereby, more precisely measured lines of the spectrum are directly given more weight in the temperature determination process. Details of the data reduction scheme are given in Ref. 2.

It is easily shown that the specie number density, N, is determined using

$$N = C_2 I_T \sum_{J=0}^{J_{max}} g_J(2J+1)e^{[-J(J+1)\theta_R/T_R]} \Big/ \sum_{J=0}^{J_{max}} T_J g_J[(J+1)(J+2)/(2J+3)]e^{[-J(J+1)\theta_R/T_R]} \qquad (2)$$

where I_T is the sum of the experimental values of I_J over all observed transitions, and C_2 is a constant determined by in-situ calibration.

Flowfield measurements were conducted in the von Karman Facility 4x10 ft. Research Chamber. Gas sources used were either a sonic orifice of exit diameter D of 1.325 mm or a conical nozzle of 1.04 mm throat diameter. The sources were mounted on an x-y-z motor-driven traversing mechanism to provide flowfield profile studies with stationary optical instrumentation, and x is taken to be the axial flow direction.

The light source was an argon ion laser nominally operated at a power level of 1.5 w at 514.5 nm. The beam was expanded and focused into the center of the chamber thereby providing a cylindrical scattering volume of approximately 50 μm diameter. The magnification of the collection optics was such that a 1.5 mm length of the scattering volume was observed, and the collection solid angle was 0.196 sr. A double spectrometer with 1200g/mm, 500 nm blaze gratings, and silvered mirrors was scanned at speeds of 0.05 to 0.2 nm/min with slit widths of 50 to 200 μm. Signal detection was provided by a cooled photomultiplier the output of which was processed by a photon counting system.

Figure 1 shows the measured axial variation of rotational temperature for N_2 reservoir pressures P_o of 2.8, 3.72, 5.58, and 7.44 atm. For $x/D < 9$ there is good agreement between the measured values and values calculated using the Ashkenas-Sherman equations.[3] For P_o values of 5.58 and

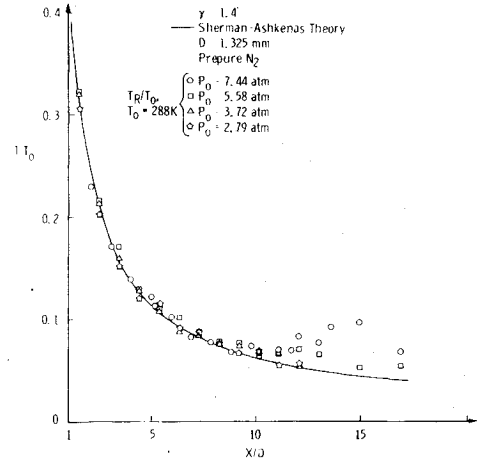

Fig. 1 Axial variation of N_2 rotational temperature in sonic orifice flow.

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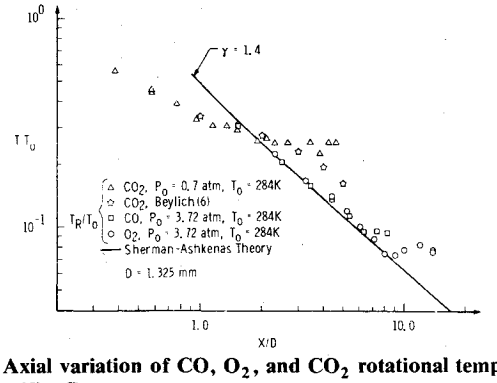

Fig. 2 Axial variation of CO, O_2, and CO_2 rotational temperature in sonic orifice flow.

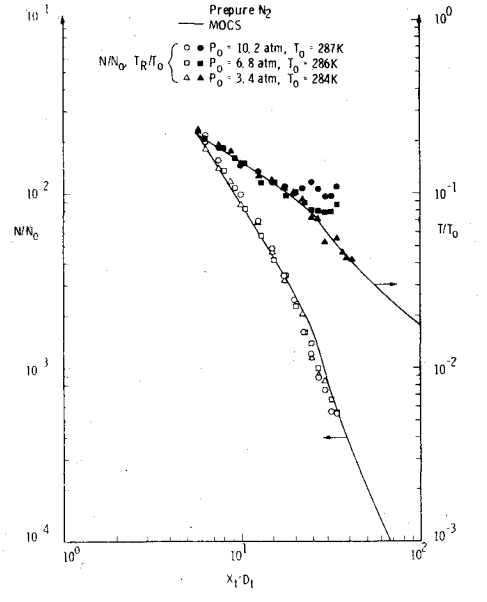

Fig. 3 Axial variation of N_2 rotational temperature and number density in nozzle flow.

7.44 atm the measured temperatures show a significant increase relative to the calculated values for $x/D>9$. For these high pressures and axial positions Rayleigh scattering measurements have shown the occurrence of massive condensation.[4] The effects of condensation are discussed in Refs. 2, 4, and 5.

The axial variation of T_R for sonic orifice pure gas expansions of CO, O_2, and CO_2 is shown in Fig. 2. For CO and O_2 there is excellent agreement between measured and calculated temperatures for $x/D<7$. Again the effects of condensation are observed to significantly increase the measured T_R for large values of x/D. For CO_2 there is no agreement with the predicted theoretical variation of T_R in the limited axial region of the measurements for $\gamma=1.4$. Agreement was obtained with the electron beam results of Beylich[6] when appropriate reservoir scaling laws were used.[7]

The axial variations of measured values of T_R and N for an N_2 conical nozzle expansion are shown in Fig. 3 for P_o values of 3.4, 6.8, and 10.2 atm. Denoting distances from and characteristic dimensions of the nozzle throat by the subscript t, it is seen from Fig. 3 that the method of characteristic solution (MOCS) predicts a discontinuity in the axial distance derivative of N and T_R at $X_t/D_t \simeq 25$, and this is due to the expansion effects from the nozzle lip. The measured axial variations of N are in good agreement with the MOCS prediction except for the region near $X_t/D_t \simeq 25$. For this axial position region it is seen that the experimental results are 30-40% lower than predicted, showing that the discontinuity in slope is not realized in practice. T_R/T_o results are in good agreement with the MOCS prediction for the $P_o = 3.4$ atm expansion for all X_t/D_t and also for the $P_o = 6.8$ and 10.2 atm expansions for X_t/D_t prior to condensation onset.[5] Significant increases (as much as 50%) in T_R/T_o due to the release of the heat of recombination in regions of massive condensation[5] can be seen in Fig. 3.

For radical distance $0 \leqslant r/D_t \leqslant 6$ profiles of N/N_o and T_R/T_o were measured. N/N_o is systematically lower than the MOCS prediction whereas the T_R/T_o results are greater than predicted for $r/D_t > 4$. Even though condensation may be only moderate on the centerline, Rayleigh scattering measurements[5] have shown more condensation off the centerline at these axial positions, and this may explain the higher than calculated temperatures at positions off the centerline.

Measured values of rotational temperature have ranged from 131K to 11K, and the range of gas number density at which the temperatures were measured was from $9.9\text{x}10^{18}$ to $2.3\text{x}10^{16}$ molecules/cm^3. At these respective number densities, the experimental uncertainty in T_R was ± 2 and $\pm 20\%$. Accurate measurements of the gas number density were obtained over the number density range of $5.7\text{x}10^{18}$ to $6.0\text{x}10^{16}$ molecules/cm^3.

These measurements are the first application at AEDC of Raman scattering diagnostics of flowfield temperatures and number density. Optical system improvements such as multiple passing the laser beam or employing an intra-cavity arrangement, using bilateral collection optics, and commercially available increased laser power can reduce the imprecision of these experiments to less than $\pm 1\%$ and decrease the lower density limit for measurements to the 10^{13} molecules/cm^3 region.

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