Laser-Raman Optical Multichannel Analyzer for Transient Gas Concentration Profile and Temperature Determination

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Abstract

IN the field of gasdynamics, the laser-Raman technique is a useful diagnostic tool as a probe[1-3] for transient measurement of the gas concentration profile and flame temperature. An optical multichannel analyzer (OMA), which enabled us to record simultaneously the spatially distributed Raman intensity or the frequency distributed Raman spectrum with 0.01-mm or 0.12-nm resolution, respectively, is discussed. Presented are laser-Raman results on the gas concentration profile of a jet emerging from a nozzle and the average gas temperature within a stable flame.

Contents

A ruby laser (694.3 nm) provided the incident radiation (1-15 J) of 1-ms duration, and the spectrograph was a Spex 1400 double monochromator modified as follows: 1) the original gratings were replaced by two plane holographic gratings of 1800 g/mm for improved stray light rejection; 2) the intermediate slit was opened to 2 cm; and 3) the exit slit was totally removed. Our OMA,[4] which is similar to that of Smith,[5] consists of a three-stage electrostatic image intensifier (Varo 8606) coupled by fiber optics to an image isocon TV camera (RCA 4807A), both cooled to $-20°C$. A computer controlled the read-beam format of the TV camera and stored the video output. Overall performance characteristics of the OMA are: 1) quantum-limited sensitivity; 2) 200 resolvable lines under quantum-limited illumination; and 3) dynamic range of about 50.

Figure 1 shows the experimental configuration for the concentration profile measurement of a jet of Freon-12 (CF_2Cl_2 with 677 cm^{-1} vibrational frequency) exiting into the air from an open or obstructed tube (3.18-mm o.d., 1.52-mm i.d., and 152.4-mm long). The laser is focused by a biconvex lens (6-cm focal length) forming a vertical image along the y axis approximately 2 mm in length and 0.1 mm in diameter. A dielectric concave mirror (with a reflectance of 99.96% at 694.3 nm) of 10-cm radius of curvature redirects the radiation into the focal volume, which, in turn, is imaged by the collection optics onto the entrance slit of the spectrograph tuned to the Raman wavelength of CF_2Cl_2. The spatially resolvable element in the focal volume is approximately 0.01 mm in the y direction and 0.1 mm in the x direction. The TV camera is scanned horizontally, accumulating the Raman photoelectrons along each horizontal line and storing the sum in a different computer address for each scan line.

The open-jet results are shown in Fig. 2 for 10-psig tank pressure (exit velocity about 0.94 Mach number and 1.2×10^5 Reynolds number) as a function of x downstream from the nozzle. Each Freon-12 Raman histogram (averaged over five separate laser firings) is a display of gas concentration vs position in the focal volume. The horizontal scale is calibrated by the 1.5-mm i.d. of the nozzle, while the vertical scale is about 10^4 photons for the well-defined Freon-12 flat-top peak which, due to diffusion and mixing with the air, evolves into a bell-shaped curve as measurements are made further downstream from the nozzle.

Temperature determination in a flame is based upon the Raman scattering vibration-rotation signatures.[6] The Q-branch spectral structure for diatomic molecules consists of a series of bands corresponding to the vibrational transitions for which the vibrational quantum number v changes from $0\rightarrow1$, $1\rightarrow2$, etc. (Stokes series) and from $1\rightarrow0$, $2\rightarrow1$, etc. (anti-Stokes series). Our aim was to detect with a single laser firing the entire Q-branch spectrum (about 5 nm) of N_2 in the flame, averaged over the 2-mm long by 0.1-mm diam focal region. By choosing the TV camera scan format to accumulate photoelectrons along vertical lines, the Raman intensity can be simultaneously detected at different wavelengths, as dispersed by the spectrograph.

The more conventional method for determining the vibrational temperature is by taking the anti-Stokes to Stokes band intensity ratio.[1] Use of the OMA to measure this intensity ratio was not attempted, because of the extremely strong Rayleigh and Mie scattering which would have occurred in the middle of the Stokes/anti-Stokes spectra.

The experimental configuration for the flame temperature measurements is similar to that of Fig. 1. The vertical laser track (along the y axis) passes through the center of the torch, which consists of a water-cooled, horizontal (along the x axis), porous plug burner[6] (2.5-cm diam) placed 2 cm away

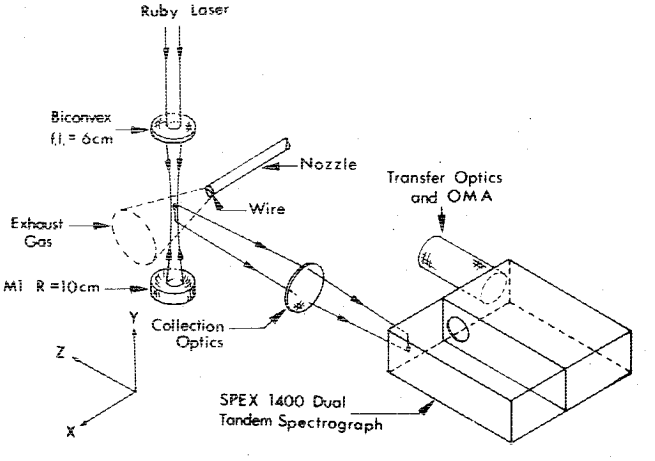

Fig. 1 Experimental configuration to measure the concentration profile of gas exiting into air from an open or obstructed nozzle.

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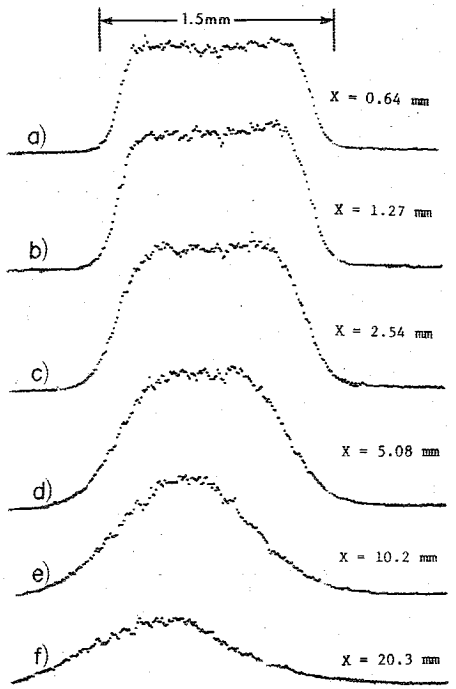

Fig. 2 Freon-12 concentration profiles from an open nozzle (see Fig. 1) as determined by the Raman Stokes intensity along the *y* axis. The distance downstream *X* is marked on the right-hand side of the figure.

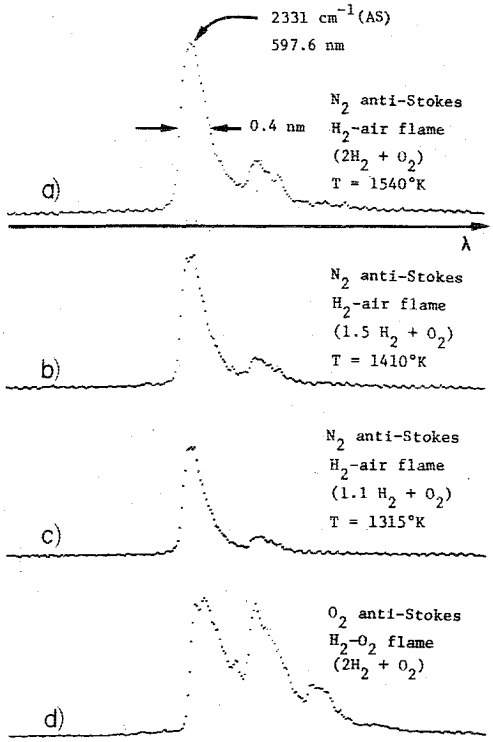

Fig. 3 a-c) The N_2 anti-Stokes series for various burner conditions. The H_2 and O_2 ratio and the temperature deduced from the band-area method are labeled; d) the O_2 anti-Stokes series at a fixed H_2 and O_2 ratio.

from a receptor (3.2-cm diam) of similar construction. The receptor is connected to a vacuum source (water aspirator drawing 175 mm Hg). The steady stoichiometric hydrogen-air flame utilized flow rates of 37.5 cm^3 H_2 and 88.8 cm^3 air, for which 65% of the product gases were N_2.

Without any laser beam, we detected a copious amount of flame luminescence in the region where the N_2 Stokes series would have occurred, whereas the flame luminescence in the region of the N_2 anti-Stokes series was considerably less. We chose to detect the N_2 anti-Stokes series centered at 597.6 nm. Our results, averaged over 20 separate laser firings, are shown in Fig. 3 for various burner conditions.

The temperatures indicated in Fig. 3 were obtained by a simple band-area method proposed by Lapp.[6] Thermocouple measurement of the flame temperature was not performed, since our primary interest was to demonstrate the feasibility of the OMA for detecting with a 1-ms pulse the vibration-rotation series. Our data (Fig. 3a) agree remarkably well with those obtained by Lapp[6] with a cw argon-ion laser, photomultiplier, spectrometer, and a complete theoretically calculated profile fit to their Raman data. For Figs. 3b and 3c, the hydrogen flow rate was decreased below the stoichiometric mixture of Fig. 3a, and a corresponding decrease in the burner temperature was deduced from the band-area method. Using a mixture of H_2 and pure O_2 gas, we were able to detect the O_2 anti-Stokes series (spectrograph centered at 626.6 nm), as shown in Fig. 3d. The three O_2 anti-Stokes peaks correspond to the $1\rightarrow0$, $2\rightarrow1$, and $3\rightarrow2$ vibrational transitions. The limited dynamic range of the video preamp in the OMA is immediately apparent, since the $1\rightarrow0$ peak should be more than twice as large.

The results presented on the concentration profile of a gas jet and the flame temperature of a burner are the first of their kind. Extension to two-dimensional recording will be possible once the OMA is modified to digitize the photoelectrons within each pixel. In principle, we will then be able to determine the transient flame temperature at each point along the laser track. Furthermore, by using cylindrical lenses to form a sheet of laser radiation, we will be able to map out the transient concentration in the *yx* or *yz* plane. In order to observe turbulence in gas jets, the duration of the laser pulse must be reduced to the 1-μs range.[7] To observe nonequilibrium temperature processes, where the vibrational and rotational temperatures can be different, an even shorter laser pulse is required.[8] The use of such short pulses will not affect the operation of the OMA, as long as sufficient laser energy can be delivered to the focal volume.

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