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# Simultaneous measurements of velocity, temperature, and pressure using rapid cw wavelength-modulation laser-induced fluorescence of OH

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**The beam from a rapid-tuning single-frequency laser was used to probe the $R_1(7)$ and $R_1(11)$ $A\ ^2\Sigma^+ \leftarrow X\ ^2\Pi$ (0, 0) line pair of OH at a 45° incident angle in a combustion-driven, supersonic free jet. Absorption line shapes were recorded in spatially resolved, single-point fluorescence. The Doppler shift, intensity ratio, and collisional broadening of the measured line pair were used to determine velocity, temperature, and pressure. The repetition rate of the measurement was 3 kHz.**

In high-speed flows, laser-induced fluorescence (LIF) of Doppler-shifted transitions is an attractive technique for velocity measurement. LIF velocimetry has been applied to combined single-point measurements of velocity, temperature, and pressure[1] and to two-dimensional imaging of velocity and pressure.[2] Prior to recent research using NO,[3] LIF velocimetry in combustion-related flows relied largely on the use of seed molecules. In this Letter we report simultaneous, single-point LIF measurements of velocity, temperature, and pressure using the naturally occurring combustion species OH.

This experiment is an extension of earlier research in which a modified ring dye laser was used to make time-resolved temperature measurements behind reflected shock waves by using OH absorption[4] and in postflame gases by using OH LIF.[5] A pair of fused-silica rhombs mounted on a single galvanometer in an intracavity-doubled Spectra-Physics 380 ring laser permit the UV output to be swept continuously over a few wave numbers at an effective frequency of 3 kHz.[6] The laser is tuned to scan the OH $R_1(7)$ and $R_1(11)$ $A\ ^2\Sigma^+ \leftarrow X\ ^2\Pi$ (0, 0) line pair at 32 625 cm$^{-1}$, and the excitation line shape is recorded in fluorescence. The component of velocity along the beam is obtained from the Doppler shift measured relative to the unshifted lines in a stationary OH source. The temperature is determined from the intensity ratio of the $R_1(7)$ and $R_1(11)$ lines, and pressure is inferred from the collisional broadening.

Measurements were performed in a supersonic (underexpanded), axisymmetric free jet, created by exhausting the products from a high-pressure, stoichiometric $CH_4$–air combustion chamber through a 1.6-mm-diameter nozzle into ambient air. After accounting for frictional losses in the nozzle, the jet stagnation pressure was estimated to be 4 atm. The gas leaves the nozzle at Mach 1 and 2.2 atm and continues to expand isentropically to a pressure less than ambient; an oblique shock then returns the gas to above ambient pressure. The process is repeated (with decreasing amplitude), resulting in a steady, diamond shock pattern.[2,7] Qualitatively, the variations in temperature follow those of pressure and are out of phase with those of velocity and Mach number. OH is created as a combustion product and is kinetically frozen during the expansion process to a superequilibrium level of approximately 0.1%.

Figure 1 shows the experimental arrangement. The laser provided approximately 15 mW of UV power, of which approximately half reached the jet. The undoubled output of the laser was passed through a fixed, 2.00-GHz visible étalon to provide a frequency marker as the laser was scanned in wavelength. The UV output was focused to less than 0.3 mm in diameter in the jet at an incident angle of 45° relative to the flow. Broadband fluorescence was collected orthogonal to the jet and the beam and was directed through a Schott UG-5 filter onto a photomultipler tube (PMT). A drilled aperture in front of the PMT defined a spatial resolution of 0.33 mm. A portion of the main beam was extracted before it entered the jet and was directed onto a detector (Det. A) to provide a laser intensity reference signal ($I_0$). A second beam was

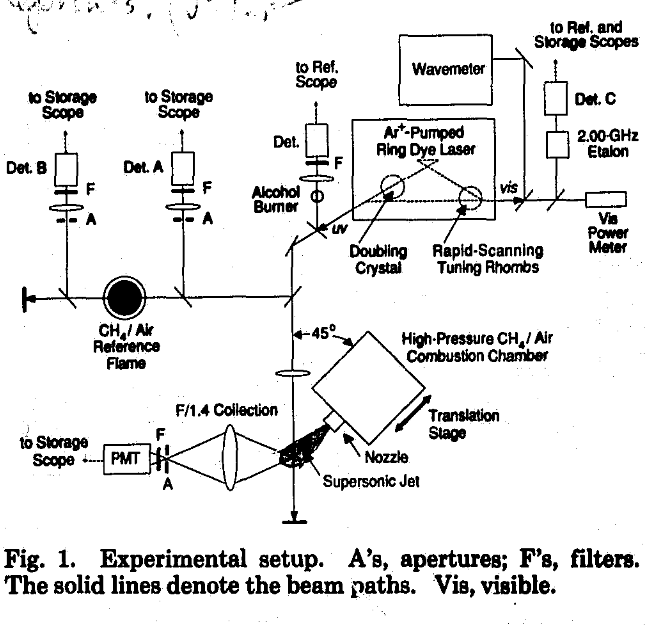


Fig. 1. Experimental setup. A's, apertures; F's, filters. The solid lines denote the beam paths. Vis, visible.

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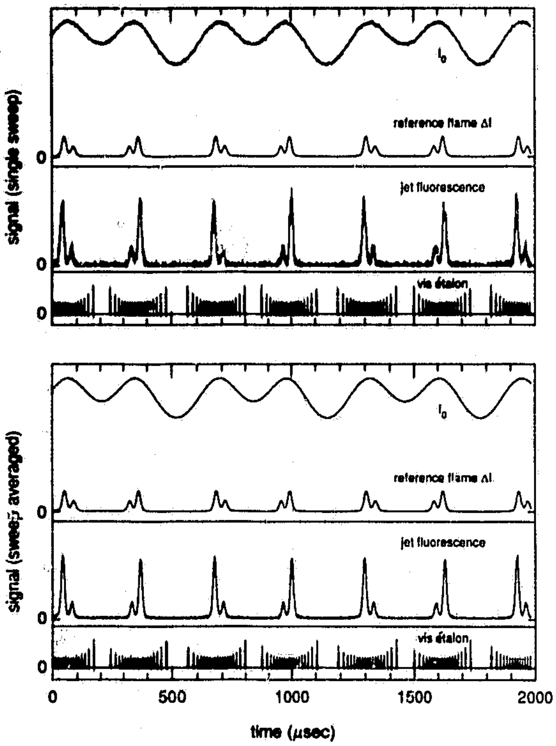


Fig. 2. Raw data traces showing both single-sweep and sweep-averaged (40 sweeps) records of scan over the OH $R_1(7)$ and $R_1(11)$ line pair at 32 625 cm$^{-1}$, simultaneously recorded in absorption in the reference flame and in fluorescence from the jet. Vis, visible.

passed over an atmospheric $CH_4$–air burner onto a second detector (Det. B) to provide an unshifted OH absorption signal ($I$). The beams were sampled by using front surface reflections off fused-silica plates and were balanced optically by varying the beam-splitter angles. The difference signal ($\Delta I = I_0 - I$) was directly recorded. Data were recorded on a four-channel, 400-kHz-bandwidth digital oscilloscope that had the option of wave-form averaging so that both single-sweep and sweep-averaged data records could be acquired.

Figure 2 shows the raw data obtained with both single-sweep and sweep-averaged methods, averaged over 40 sweeps. The top panels for each case show the reference signal $I_0$ and the absorption signal $\Delta I$ from the reference flame. The $R_1(7)$ and $R_1(11)$ lines alternate in order as the laser wavelength is scanned back and forth in time; the higher of the peaks is that of the $R_1(7)$ line. The center panel shows the signal acquired simultaneously from the PMT above the jet, obtained on the jet centerline at a distance of 2.2 mm ($x/D = 1.4$) downstream from the nozzle exit. The PMT signal is a superposition of fluorescence from OH and a small background signal (scattering from flow particulates) that is on average proportional to the incident laser intensity. The lower panel shows the étalon signal that is used to convert the time axis to frequency.[6]

Figure 3 shows normalized line shapes obtained from the single-sweep and sweep-averaged traces of Fig. 2. The flame absorption data are proportional to $\ln(1 - \Delta I/I_0)$. For each data set, the frequency position corresponding to zero shift is determined by a fit to the flame data (these fits indicate a reference flame temperature of 1750 K). The jet fluorescence data are corrected for background scattering and the variation in $I_0$ and are fitted to profiles. The profiles are calculated by using shift, temperature, and collisional broadening as fitting parameters, while the integrated area of the profile is fixed to that of the data. The best fit is that which minimizes the integral of the squared difference between the calculated and measured profiles.[5,8] The reported uncertainties in the fitting parameters are those that correspond to a 30% increase in this integrated difference.

The Doppler shift is linear with velocity, with a proportionality constant of 306.5 m/sec per gigahertz at the OH wavelength. The shift of 2.9 GHz shown in Fig. 3 corresponds to a velocity of 890 m/sec along the direction of beam propagation (or a centerline velocity of 1260 m/sec). Fitting uncertainties are ±0.25 GHz (75 m/sec) for the single-sweep case and less than ±0.1 GHz (30 m/sec) for the sweep-averaged case. However, electronic rise times of 0.5 μsec combine with the scan rate to lead toward possible errors of as much as 0.1 GHz. The effects of collision-induced line shifts must also be considered. Limited pressure–shift data available for OH give a collision width-to-shift ratio of 12 for room-temperature air.[9] If this ratio is assumed for the postcombustion gases, a maximum of 0.1 GHz is calculated for the difference between collision shifts

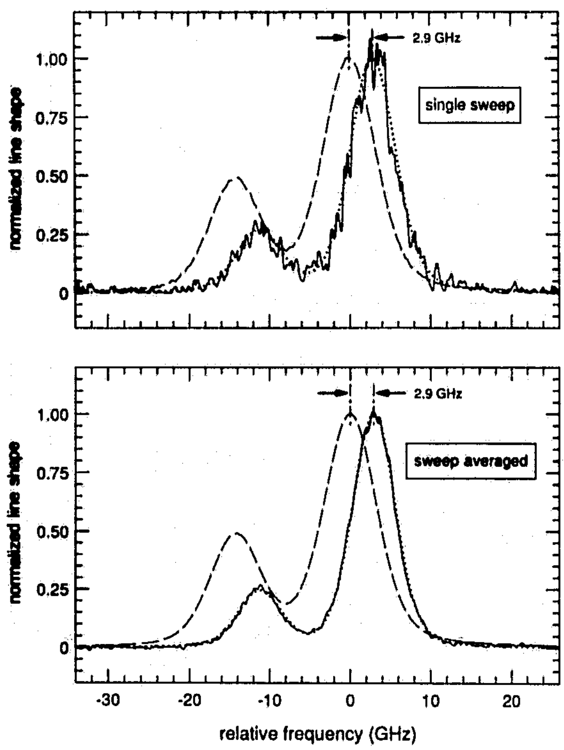


Fig. 3. Reduced data for both single-sweep and sweep-averaged scans showing the first complete line pairs (at 350 μsec) of Fig. 2. The 2.9-GHz line shift corresponds to 890 m/sec. Solid curves, jet fluorescence data; dashed curves, flame absorption data; dotted curves, best fit to jet fluorescence data.

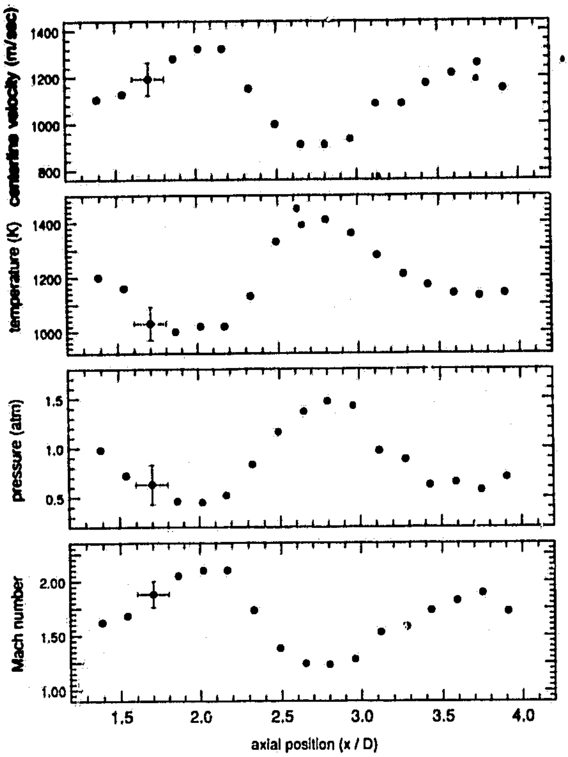


Fig. 4. Jet centerline conditions measured from sweep-averaged profiles (25 sweeps). $D = 1.6$ mm.

in the jet and reference flame. Total uncertainties in the measured velocity component are estimated to be ±90 m/sec for the single-sweep data and ±50 m/sec for the sweep-averaged data.

As in previous experiments, the temperature is determined through the Boltzmann intensity ratio of the two lines.[4,5] The fitting procedure recovers the temperature that best matches the intensity ratio of the recorded data. The single-sweep and sweep-averaged profiles of Fig. 3 yield temperatures of 1130 and 1080 K, respectively, with fitting uncertainties of ±150 and ±40 K. Because the data are acquired in fluorescence, factors such as radiation trapping and incomplete rotational redistribution of the upper levels must be considered. In these experiments, the former effect is negligible, as the total peak absorption across the jet was less than 3%. The latter effect adds to the measurement uncertainty, although in principle a correction could be performed.[5] The total uncertainties in the measured temperature are estimated to be ±160 K for the single-sweep data and ±60 K for the sweep-averaged data.

In the jet, Doppler broadening dominates collisional broadening by a factor of 3 to 7. Thus a good signal to-noise ratio (as well as a good knowledge of temperature) is critical for a pressure measurement. Pressure-broadening coefficients for flame gases at combustion temperatures are reasonably well known, with uncertainties of the order of 15%.[8] We used a correlation of Voigt a (the ratio of collisional to Doppler broadening) $= 0.20P\,(\text{atm}) \times [1600/T\,(\text{K})]^{1.3}$ for $CH_4$–air combustion products, based on previous research.[5,8] From the fits of Fig. 3, pressure values of 0.83 and 0.60 atm are obtained for the single-sweep and sweep-averaged profiles, respectively, with fitting uncertainties of ±0.35 and ±0.1 atm (including the affect of the uncertainty in temperature). Total uncertainties in the measured pressure are estimated to be ±0.4 atm for the single-sweep data and ±0.2 atm for the sweep-averaged data.

Figure 4 shows measured centerline velocity, pressure, temperature, and Mach number (calculated from the measured velocity and temperature) obtained from reducing sweep-averaged profiles (25 sweeps) acquired at different axial locations along the jet centerline. The measurements show the expected cell structure of a diamond shock pattern, and the values are consistent with measurements in similar jets.[2,10] The shocks themselves occur at axial locations $(x/D)$ of 2.2 and 3.8. An isentropic analysis of the data in the expansion region before the first shock recovers a stagnation pressure of 4.3 atm, which is consistent with the value of 4 atm obtained by using correlations based on the observed 1.6 $(x/D)$ shock separation.[7,10]

To our knowledge, these measurements represent the first use of LIF to perform Doppler velocimetry in a combustion environment. Simultaneous measurements of temperature and pressure were obtained through the recording of fully resolved Doppler-shifted line shapes. Although many of the results presented here were obtained with a time-averaged method, the potential was demonstrated for kilohertz acquisition rates, as was utilized in previous research.[4,5] The large uncertainties in the single-sweep data are a reflection of low signal-to-noise ratio, which could be improved by degrading the spatial resolution and by reducing the interference scattering. A clear extension of the present technique would be the use of the absolute intensity of the fluorescence for simultaneous measurement of species concentration.

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