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Flow Visualization in Combustion Gases Using Nitric Oxide Fluorescence

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Introduction

A TECHNIQUE using imaging of planar laser-induced fluorescence (PLIF) for quantitative, simultaneous multiple-point measurements of the OH concentration in flames has recently been reported.[1,2] Measurements of this type have potential for elucidating the interactions between the chemistry and fluid mechanics of combustion flows. In this Note a further extension of the technique, making use of NO fluorescence, is described. This work was motivated partially by the desire to investigate the suitability of NO as a seed material for visualizing species concentration and temperature (for example in mixing studies) and partially by an interest in NO kinetics.

Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. The frequency-doubled output of a Nd:Yag-pumped dye laser was mixed with the residual 1.06 μm beam of the Nd:Yag laser in a KDP crystal to obtain output near 225 nm. A vertical sheet (6-16 cm high and 0.2 mm thick) of the laser output (~ 1 mJ/pulse) was transmitted across the flowfield under study. Detection of the resulting fluorescence was accomplished using an image-intensified Reticon MC520/RS520 camera system containing a 100×100 photodiode array. A color glass filter (Schott glass UG-5) mounted in front of the camera was used to reduce stray and scattered light. In some experiments an additional interference filter ($\lambda = 252$ nm, bandwidth $= 24$ nm) was used to eliminate the influence of flame luminosity and scattered light. The output of the photodiode array was digitized using a Data Translation 2782 A/D converter interfaced with an LSI 11/23 computer. A more detailed description and discussion of the sensitivity of the system has been reported previously.[3]

Two combustor flowfields were used in this feasibility study. The first was an atmospheric pressure, laminar premixed CH_4/air flame stabilized on a 7-cm-diam flat flame burner. The second combustor flowfield was an atmospheric

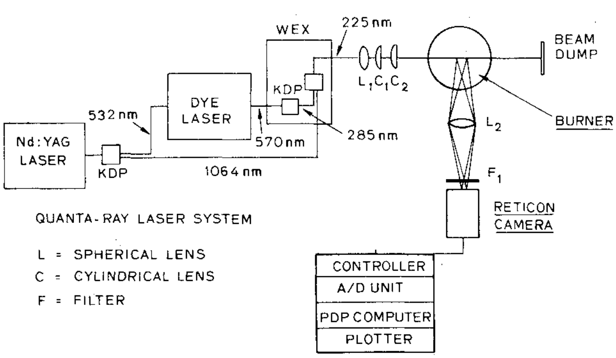

Fig. 1 Experimental setup.

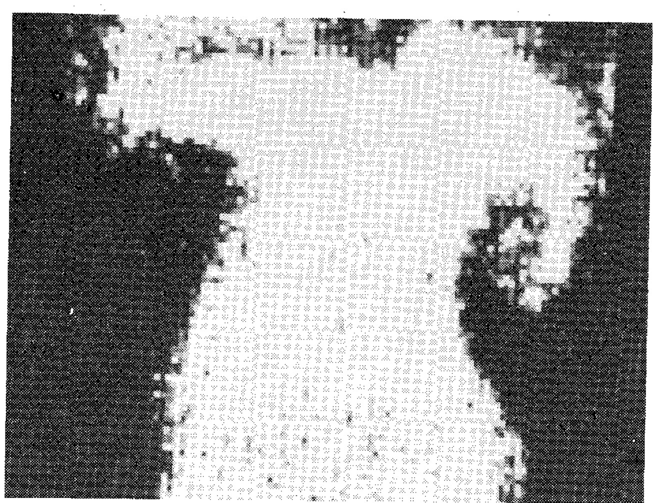

Fig. 2 Single-shot digital picture of NO mole fraction distribution in a laminar, premixed CH_4/air flame. NO seed level is 1900 ppm in the inlet flow. Each pixel indicates the level of fluorescence from a volume $0.8 \times 0.8 \times 0.2$ mm in size. Laser was tuned to the $Q_1(35)$ line of NO so that the intensity levels are indicative of the mole fraction in the flowfield.

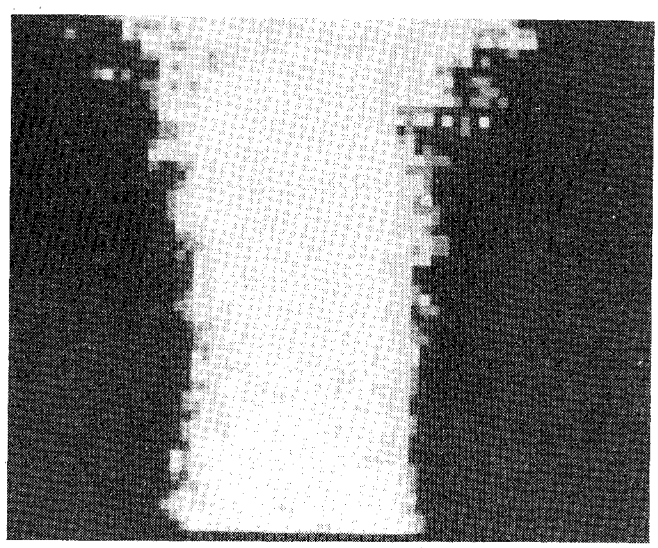

Fig. 3 Single-shot digital picture of NO concentration distribution in a turbulent, premixed CH_4/air flame. Each pixel indicates the level of fluorescence from a volume of $0.8 \times 0.8 \times 0.2$ mm in size. NO premixed to main flow with a seed level of 3800 ppm. Laser was tuned to the $Q_1(35)$ line of NO.

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pressure, turbulent premixed CH_4/air flame (Reynolds's number approximately 5000 based on the tube diameter of 1.3 cm), stabilized by means of a thin, coaxial CH_4/air diffusion flame.

A number of digital pictures of the flow patterns were recorded using different NO seed levels (premixed into the fuel/air flow), different excitation wavelengths, and different fields of view.

Theory

Assuming weak excitation by a broadband laser source, the fluorescence signal S_F can be related to the NO total number density N_{NO} via the equation:[4]

$$S_F = CI\frac{A_{21}}{A_{21}+Q}f_p(T)B_{12}N_{NO} \tag{1}$$

where C is a constant that includes geometrical and efficiency factors, I is the laser spectral irradiance, $A_{21}/(A_{21}+Q)$ is the photon yield or Stern-Vollmer factor, Q is the electronic quenching rate, A_{21} and B_{12} are the Einstein coefficients for the transition, and $f_p(T)$ is the fraction of NO in the state being pumped.

The proportionality factor between the fluorescence signal and the total NO number density can be regarded as a constant provided that the product of the Stern-Vollmer factor and the population factor does not vary significantly throughout the flowfield being studied. This can often be accomplished by choosing a molecular transition with an appropriate temperature dependence in the population factor. Alternatively, a transition may be selected so that there is a nearly constant relation between S_F and NO mole fraction. If a measurement of temperature is the goal (for example in a flow with fixed NO mole fraction) a transition with a strong, known temperature dependence may be selected.

Two different laser wavelengths ($\lambda = 225.598$ and 224.526 nm) were chosen corresponding to the $R_1(16)$ line and the $Q_1(35)$ line of the $A^2\Sigma^+ (v=0) - X^2\Pi_{1/2} (v=0)$ band of NO. The fluorescence signal arising from excitation of the $R_1(16)$ line is temperature insensitive (estimated change of $\pm 10\%$ in $f_p A_{21}/(A_{21}+Q)$ between 500 and 2000 K), so that the measured fluorescence intensity distribution is expected to be proportional to the NO number density distribution. Similarly, excitation of the $Q_1(35)$ line provides a signal proportional to the NO mole fraction in the temperature range 1100-2400 K.

Results

Figure 2 is a single-shot digital picture of the fluorescence signal generated in the plane of illumination of the laser, above the stoichiometric CH_4/air flat flame burner. The laser was tuned to the $Q_1(35)$ line of NO providing 0.9 mJ/pulse with a bandwidth of approximately 0.5 cm^{-1} and pulse duration of about 8 ns. The NO seeding level was 1900 ppm in the inlet gas stream. The fluorescence intensity is seen to be nearly constant in the inner part of the flame, as expected, since no mixing has occurred with the surrounding air. The local variations in signal that are observed in this core region are thought to be due to pixel-to-pixel variations in responsivity and shot noise. At the edges of the flame, diffusion and mixing reduce the NO mole fraction, resulting in reduced fluorescence. The large-scale structures produced at the unstable boundary between the hot flame gases and the cool surrounding air are clearly visualized in these records, indicating the potential of this diagnostic technique for quantitative studies of such phenomena.

Figure 3 shows digital pictures of the NO fluorescence in a stoichiometric, premixed CH_4/air turbulent flame, with the laser tuned to the $Q_1(35)$ line. NO is premixed in the inlet flow with a mole fraction of 3800 ppm. Background emission (due to the luminosity of the flame) was eliminated by subtraction of two frames with the laser on and off, respectively. Owing to the much higher Reynolds number of this flame, the NO signal corresponds more nearly to that of a jet with constant mole fraction in the inner core independent of combustion reactions. The different character of the mixing regions at the boundaries of the flame gases, relative to the low-speed flame shown in Fig. 2 is clearly apparent.

Conclusions

Planar laser-induced flourescence (PLIF) with a Reticon array imaging system has been used to visualize NO in combustion flowfields with submillimeter and submicrosecond resolution. The NO was seeded to laminar and turbulent CH_4/air flames. The lowest seed level used was 350 ppm premixed with the fuel/air flows. NO levels down to 30 ppm in the outer parts of the flames were resolved on a single-shot basis. Using improved collection optics, NO mole fractions smaller than 10 ppm should be detectable.

The seeding of flows with NO overcomes some of the disadvantages of previously used seed materials such as iodine[5] (useful only in cold flows) and sodium[6] (requires heating, and uniform seeding is difficult to achieve). NO is relatively stable at temperatures up to 2000 K in many combustion environments, and therefore seems well suited for use in visualizing combustion as well as cold flows.

By choosing different NO molecular transitions it is possible to provide fluorescence distributions which vary in their sensitivity to temperature. It should therefore be possible to visualize temperature, mole fraction, and number density by pumping appropriate molecular transitions. This capability should be of importance in studies of mixing processes. Moreover the technique is sufficiently sensitive to be useful in studies of NO chemical kinetics in combustion flows.

Acknowledgments

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A Uniformly Valid Asymptotic Solution for Unsteady Subresonant Flow Through Supersonic Cascades

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Introduction

LOW-FREQUENCY approximations of unsteady flow through supersonic cascades with a subsonic leading-edge

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