

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM

---

# Optical Measurements of Fluctuating Temperatures in a Supersonic Turbulent Flow Using One- and Two-Photon, Laser-Induced Fluorescence

---

Kenneth P. Gross and Robert L. McKenzie

---

May 1984

LIBRARY COPY

JUN 1 1984

LANGLEY RESEARCH CENTER  
LIBRARY, NASA  
HAMPTON, VIRGINIA



National Aeronautics and  
Space Administration



NF00809

---

# Optical Measurements of Fluctuating Temperatures in a Supersonic Turbulent Flow Using One- and Two-Photon, Laser-Induced Fluorescence

---

Kenneth P. Gross, Polyatomics Research Institute, Mountain View, California  
Robert L. McKenzie, Ames Research Center, Moffett Field, California



National Aeronautics and  
Space Administration

**Ames Research Center**  
Moffett Field, California 94035

N84-25020<sup>#</sup>

OPTICAL MEASUREMENTS OF FLUCTUATING TEMPERATURES IN A SUPERSONIC TURBULENT FLOW  
USING ONE- AND TWO-PHOTON, LASER-INDUCED FLUORESCENCE

Kenneth P. Gross\*

Polyatomics Research Institute, Mountain View, California

Robert L. McKenzie†

NASA Ames Research Center, Moffett Field, California

Abstract

A laser-induced fluorescence technique has been developed that provides a practical means of nonintrusively measuring the instantaneous temperatures in low-temperature turbulent flows. The capabilities of the method are reviewed, and its application to a simple, two-dimensional, turbulent boundary-layer flow at Mach 2 is reported. Measurements of the average temperature distribution through the boundary layer and the magnitudes of temperature fluctuations about their average values are presented.

Introduction

At the present time, few nonintrusive diagnostic methods are available that have sufficient temporal and spatial resolution for measuring the parameters of interest in fluid dynamics research of cold, turbulent flows. Except for velocity measurements using the well-established laser-Doppler velocimetry method, laser-based techniques giving measurements of other flow field properties, such as temperature and density, have not yet been demonstrated that are adequate for the instantaneous sampling of fluctuating quantities. For example, light-scattering processes, such as Rayleigh or spontaneous Raman techniques, are generally restricted to time-averaged measurements; a result of their intrinsically low scattering cross sections and the corresponding difficulties associated with extracting the signal of interest from background noise.<sup>1,2</sup> Modern nonlinear optical methods, such as coherent anti-Stokes Raman scattering (CARS), have been successfully applied primarily to high-temperature combustion environments. However, an alternative optical diagnostic technique that can provide both temporal and spatial resolution in low-temperature fluctuating or turbulent flows is laser-induced fluorescence (LIF), as the results reported here will show.

The sensitive measurement of temperature in low-temperature flows, using LIF, requires consideration of several fundamental requirements. Those of primary importance include 1) the presence in the flow of a molecular species with absorbing and fluorescing transitions of sufficient strength to provide low-noise signals and signals that are resonant with available laser frequencies; 2) the use of spectral features that can be resolved with sufficient detail to accurately infer a temperature; and 3) the availability of sufficient information to accurately account for the effects of fluorescence trapping, collisional quenching, and other fundamental molecular processes affecting the

fluorescence signals. Generally, to obtain practical spectroscopic measurements of temperature in the range from 150 to 300 K, typical of many gas-dynamic test facilities, rotational line spectra must be used because only rotational energy differences are smaller than or comparable to the thermal energy being measured.

Here, we report the application of a laser-induced fluorescence technique, which meets these requirements, to a low-temperature supersonic turbulent flow. To our knowledge, these data are the first of their kind obtained by nonintrusive means with adequate temporal and spatial resolution for turbulent boundary-layer studies. The method, similar to that described previously,<sup>3,4</sup> requires that the flow be seeded with a low concentration of nitric oxide. It relies on the detection of the broadband ultraviolet (UV) fluorescence following laser excitation of two transitions originating from different ground-state rotational levels in the  $\text{NO}(X^2\Pi, v'' = 0 \rightarrow A^2\Sigma^+, v' = 0)$  vibronic  $\gamma$  band. Each excitation may be accomplished by using either one-photon or two-photon absorption and each is induced by a separate tunable laser with its frequency set at the molecular transition of interest. The relative energy absorbed by each transition is measured by monitoring the subsequent broadband fluorescent emission. The two laser pulses are slightly separated in time, allowing both fluorescence waveforms to be simultaneously recorded with a single detection system. Subsequent deconvolution of the double-pulse waveform allows the individual fluorescence energies to be computed. Since the fluorescence energy is proportional to the energy absorbed by the molecule for each transition, and since that in turn is proportional to the initial state number densities, the ratio of fluorescence energies for the two transitions can be related to the rotational temperature of the ground-state NO molecule through the Boltzmann relation for the rotational state number densities:

$$\frac{I_2}{I_1} \propto \frac{n_2}{n_1} \propto \exp \left[ \frac{-(E_2 - E_1)}{kT} \right]$$

where  $I_i$  is the fluorescence intensity,  $E_i$  is the ground-state rotational energy,  $n_i$  is the ground-state number density of each transition,  $k$  is the Boltzmann constant, and  $T$  is the rotational temperature. The rotational temperature thus obtained for the NO constituent is closely coupled to the kinetic temperature of the gas mixture, providing repetitive measurements of the local kinetic temperature, acquired at the laser pulse-repetition rate. Similar fluorescence measurements are also made simultaneously in a nonflowing reference cell at a known pressure and temperature to normalize the variations in fluorescence signal strength owing to pulse-to-pulse fluctuations in laser energy and spectral frequency.

\*Research Scientist.

†Research Scientist. Member AIAA.

## Experimental Method

### Wind Tunnel

The flow facility used for these experiments is a small blowdown wind tunnel consisting of a high-pressure storage reservoir at ambient temperature, a supersonic-nozzle test section, and an evacuated dump tank. The facility can handle toxic gases such as NO at low concentration levels. Up to 300 ppm NO in nitrogen was used for the two-photon LIF measurements. The boundary layer studied was produced on the lower wall of a rectangular Mach 2 nozzle. Figure 1 shows a simple schematic of the boundary-layer channel and depicts

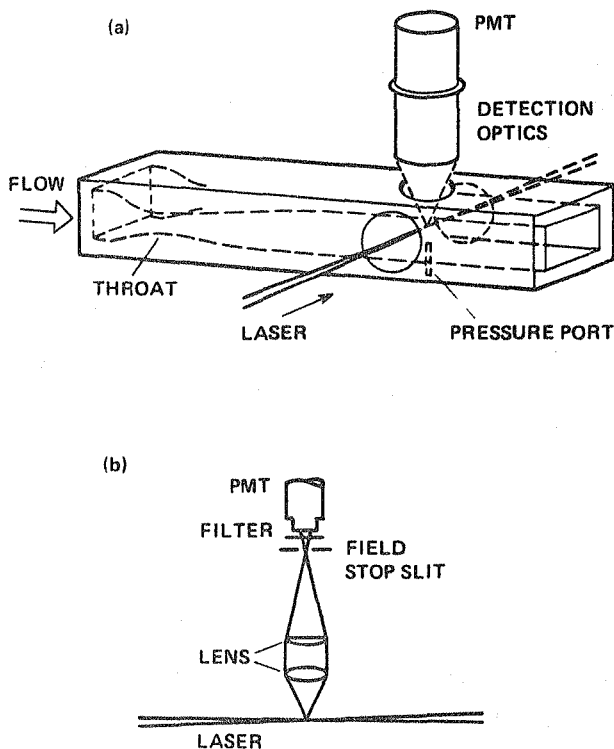


Fig. 1 Boundary-layer channel. a) Schematic of test section depicting laser access and fluorescence emission ports; b) view of light collection geometry and imaging system.

the test-section instrumentation ports and collection optics geometry used for the fluorescence measurements. The nozzle has a  $25 \times 64$ -mm exit, followed by a slightly diverging channel that extends 762 mm from the nozzle throat to the measurement ports. The facility was operated at ambient total temperature with stagnation pressures ranging from 3 to 7 atm. At a stagnation pressure of 3.5 atm, the test section contained a fully turbulent boundary layer filling the upper and lower thirds of its 33-mm height with an inviscid core flow in the center. The test time varied from between 5 and 20 sec, with the upper limit determined by reservoir stagnation pressure and dump-tank capacity. Optical access to the flow for the lasers was obtained through 50-mm-diam, fused-silica windows mounted on each side of the channel. Fluorescence was observed through a similar window on the top of the channel. Static pressure measure-

ments were made at the channel wall and a pitot tube was temporarily inserted through the top port in the test section to make extensive measurements of total pressure through the boundary layer. Shadowgraphs of the flow taken with and without the pitot tube in place indicated that the measurement volume was free from shock waves or other significant disturbances. The nominal test conditions were as follows.

Stagnation pressure,  $P_t = 3.5$  atm

Mach number,  $M_\infty = 2.03$

Stagnation temperature,  $T_t = 295$  K

Free-stream temperature,  $T_\infty = 158$  K

Boundary-layer thickness,  $\delta = 1.4$  cm

Reynolds number based on  $\delta$ ,  $Re_\delta = 6 \times 10^5$

### LIF Experiment

The optical arrangement used for the LIF measurements is illustrated in Fig. 2. Two grating-tuned dye lasers were pumped at 10 Hz by the 355-nm third-harmonic output of an Nd:YAG laser. The portion of the pump beam directed to the second dye laser was optically delayed, using two plane mirrors, giving a temporal separation of 130 nsec between the two 5-nsec dye-laser pulses. Each laser pulse was linearly polarized, and had an energy of a few millijoules contained in a spectral bandwidth of  $0.2$ – $0.3$   $\text{cm}^{-1}$ .

For two-photon LIF measurements, the first and second dye-laser pulses, at wavelengths near 450 nm, were tuned to half the transition frequencies corresponding to the  $J'' = 19 \frac{1}{2}$  and  $J'' = 7 \frac{1}{2}$ ,  $S_{11} + R_{21}$ , two-photon transitions, respectively. For single-photon measurements, each dye-laser output was frequency-doubled with potassium pentaborate (KB5) to produce UV energies of several microjoules. The single-photon transitions used were the  $J'' = 18 \frac{1}{2}$ ,  $Q_{11} + P_{21}$  line and the  $J'' = 7 \frac{1}{2}$ ,  $R_{21}$  line. In both cases the orthogonally polarized beams were made collinear, focused by a common lens with a 500-mm focal length, and partitioned in the wind-tunnel test section and reference cell. The focal spot size at the measuring point was 0.5 mm.

Broadband nitric oxide fluorescence in the spectral range from 225 to 330 nm was collected from the flow channel and reference cell with nearly identical f/1 fused-silica optics. It was transmitted through broadband UV filters and imaged through an aperture that limited the observed sample volume to a 1-mm path length along the laser beam axis. The fluorescence waveforms were detected by solar-blind photomultipliers, with peak responsivity in the ultraviolet and recorded by Tektronix 7912AD transient digitizers interfaced to an HP-1000 computer. The effective temporal resolution for each instantaneous temperature measurement was determined by the 130-nsec separation of dye-laser pulses. Spatial resolution was determined by the nearly cylindrical sample volume of approximately 0.5 mm diam by 1.0 mm in length.

Before each wind-tunnel run, static fluorescence measurements were performed with the flow channel filled with the test gas mixture at ambient

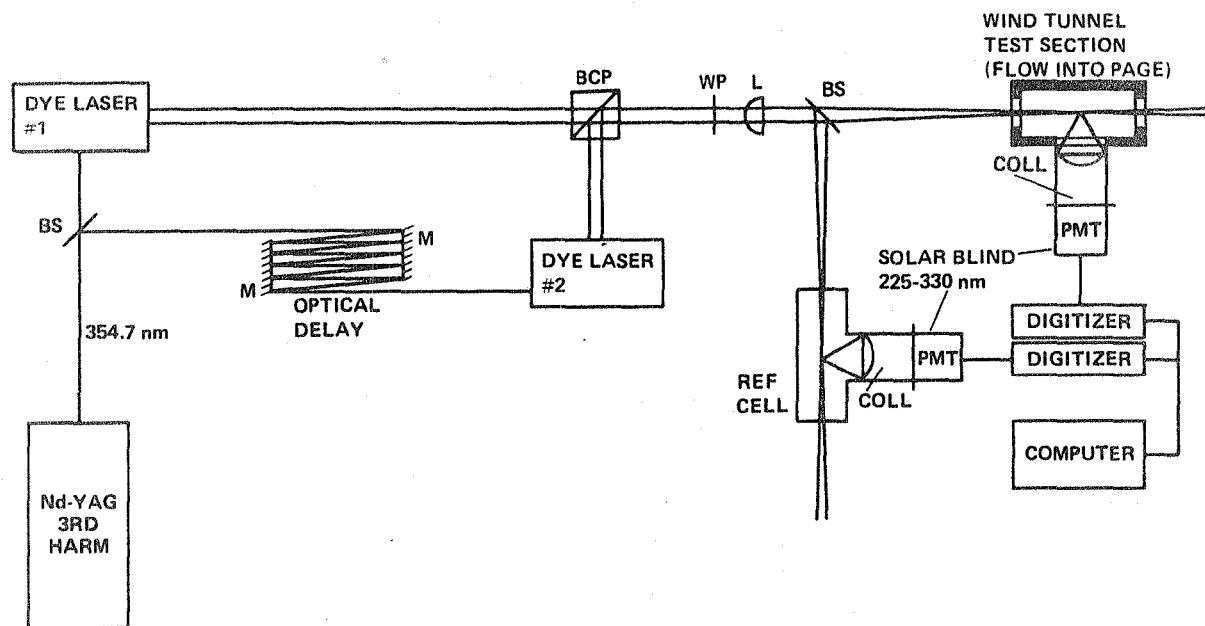


Fig. 2 Schematic of the experimental arrangement: BCP, beam-combining polarizer cube; WP, half-wave plate; L, lens; BS, beamsplitter; M, mirror; COLL, collection system; PMT, photomultiplier tube.

temperature. These pre-run tests served to calibrate the measurement system, using the known pressures and temperatures in both the flow channel and reference cell. Gas pressure in the reference cell was adjusted so that Voigt line-shape profiles were matched to those in the wind-tunnel flow. This procedure maximized the effectiveness for normalization of pulse-to-pulse variations in fluorescence signal amplitude owing to the unavoidable frequency jitter of each dye laser.

As described in Ref. 3, the data analysis leading to a temperature value for each pump laser pulse requires knowing the ratio of broadband fluorescence energies resulting from each excitation. The ratio is obtained from each double-pulse waveform by fitting it to a six-parameter function derived for an exponentially decaying emitter driven by a short excitation pulse with a Gaussian temporal profile. The two pulses in each waveform are then deconvolved and their individual integrals computed. The integral of each pulse is assumed to be linearly proportional to the total fluorescence energy resulting solely from its corresponding laser excitation, with account taken of the laser spectral width and all collision-broadened molecular transitions falling within the excitation bandwidth.

Figure 3 shows an example of some experimental fluorescence waveforms and their functional fits for typical wind-tunnel conditions using single-photon excitation. The first pulse results from excitation of the  $J'' = 18 \frac{1}{2}$  rotational level, and the second pulse is from excitation of the  $J'' = 7 \frac{1}{2}$  level. Ultraviolet laser energies were in the range of 1-3  $\mu$ J for each excitation. For an NO concentration of 100 ppm (Fig. 3a), the photon-statistical noise is very low and the signal-to-noise ratios for each pulse were approximately several hundred to one. For the weaker signals at 5 ppm (Fig. 3b), the photon-statistical noise on the waveforms is evident and easily distinguished from the computer-fitted function. The experimental

waveforms observed using two-photon excitation and 300 ppm NO had signal-to-noise ratios of about 25, also limited by photon-statistical noise.

### Results

The instrumental uncertainty for the LIF measurements was initially evaluated in a low-temperature static test cell at conditions duplicating those expected in the wind tunnel. The cell contained thermocouples located close to the laser sampling point that provided an independent measurement of the local temperature in the gas mixture. Temperature measurements performed in the static cell using two-photon excitation<sup>4</sup> are shown in Fig. 4 for a range of temperatures between 155 K and 295 K. The average temperatures calculated from 50 laser pulses are represented by the circles. The error bars indicate the corresponding rms deviation from each average value. Generally, the average spectroscopic temperatures agreed with the thermocouple to within  $\pm 2\%$ , whereas the instantaneous single-shot temperatures varied between 3% and 4% rms for each data set, thus defining the instrumental rms noise sensitivity using two-photon excitation.

Two-photon excitation of the NO  $\gamma(0,0)$  band, although easier and more convenient to implement experimentally than single-photon excitation, suffers from Stark broadening caused by the intense laser fields needed to induce appreciable absorption.<sup>4,5</sup> This effect, which manifests itself as a power-dependent broadening of the spectroscopic lines used for the measurement, defeats the use of normalization by a reference cell, and forces the measurements to be made using a minimum laser intensity with a corresponding increase in signal noise. It is this basic limitation for the two-photon process that limits the temperature measurement noise to approximately 4%. By using single-photon excitation instead of a multiphoton scheme, much higher signal levels can be achieved with much lower laser

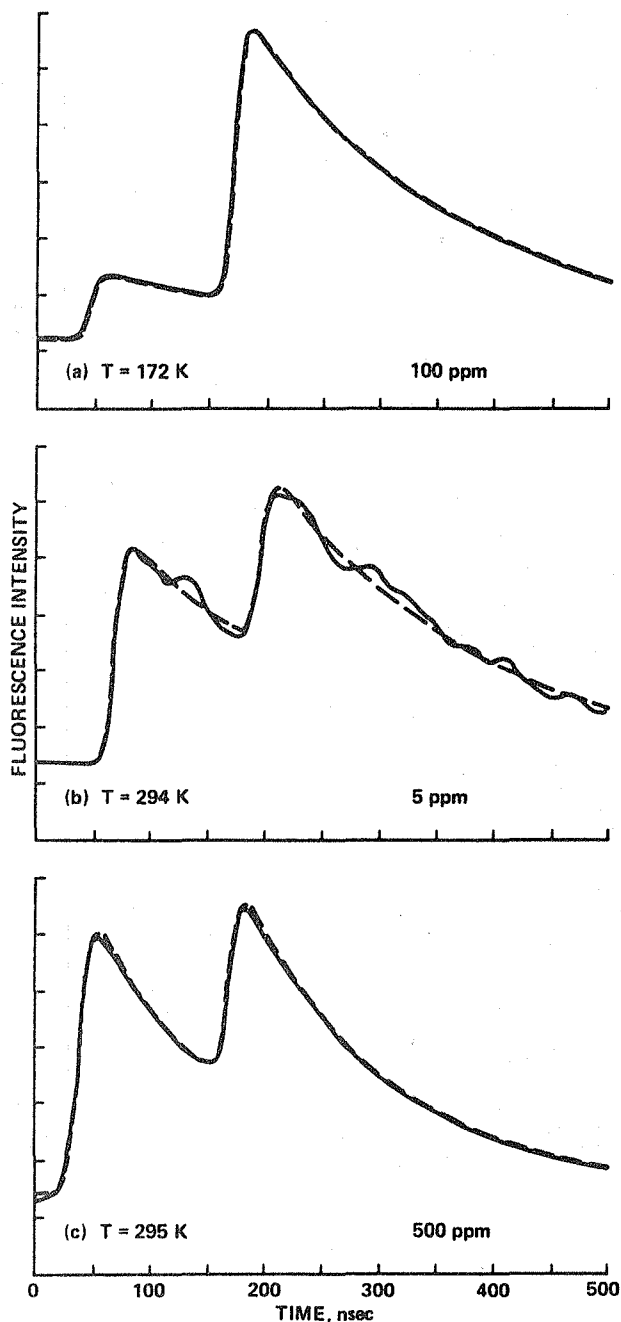


Fig. 3 Dual-pulse fluorescence waveform (solid line) and computer-fitted function (dashed line). a) Boundary-layer sample with 100 ppm NO, static pressure = 0.43 atm,  $T = 172$  K; b) room-temperature sample with 5 ppm NO in 0.5-atm  $N_2$ ,  $T = 294$  K; c) room-temperature reference cell with 500 ppm NO in 0.6 atm  $N_2$ ,  $T = 295$  K. First pulse is fluorescence from the one-photon  $Q_{11} + P_{21}$  ( $18\ 1/2$ ) excitation; second pulse is from the  $R_{21}$  ( $7\ 1/2$ ) excitation. Vertical amplifier bandwidth, 20 MHz; sweep, 50 nsec/div.

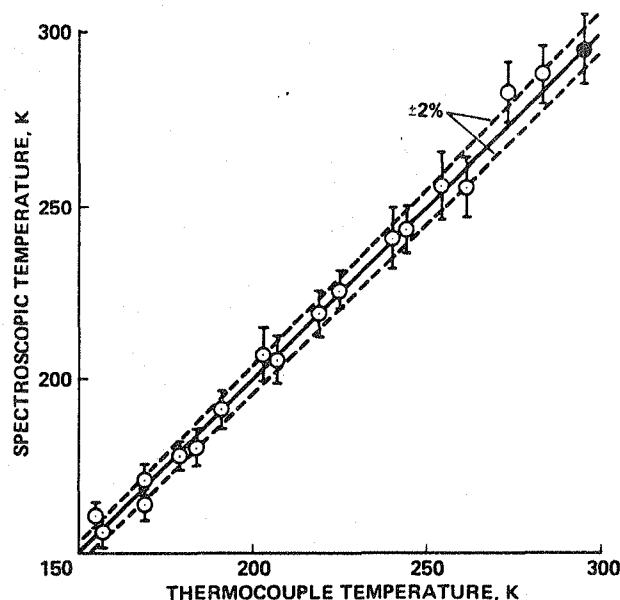


Fig. 4 Comparison of measured rotational temperature and thermocouple temperature using two-photon excitation. Cell mixture: 300 ppm NO in 0.5-atm  $N_2$ .

intensities, giving the added advantage that Stark effects are completely negligible. The primary disadvantages accompanying the use of one-photon excitation are the need for a more complicated experimental setup, the practical difficulties associated with handling and directing ultraviolet laser beams, and the rejection of scattered laser light at wavelengths close to those of the fluorescence signals. Fortunately, for the case of NO  $\gamma(0,0)$  band excitation, the single-photon-induced fluorescence signals are much larger than the stray light levels that were encountered in these experiments, allowing adequate rejection of radiation at the excitation frequency with simple band-pass filters.

The higher signal levels produced using single-photon excitation also allow a considerable reduction in nitric oxide seeding concentration. Figure 5 is a plot of temperature sensitivity versus NO concentration, using UV laser energies of a few microjoules. It shows that for nitric oxide concentrations above 50 ppm in 0.5-atm  $N_2$ , the rms noise in the temperature measurement is about 1%. At concentrations below 50 ppm, the effects of photon-statistical noise begin to increase. Nevertheless, useful measurements can still be made at concentrations of only a few ppm, although interference from scattered laser light will become a larger fraction of the total signal and may require increased spectral filtering. Single-photon measurements using concentrations of about 1-2 ppm are nearly equivalent in noise sensitivity to the corresponding two-photon measurements made using 300-ppm NO.

The results of the wind-tunnel tests are illustrated in Figs. 6 and 7. Figure 6 shows the distribution of average temperature obtained by the LIF method, as the measurement point is traversed from the channel centerline to a position approximately 0.5 mm from the wall. Both one-photon and

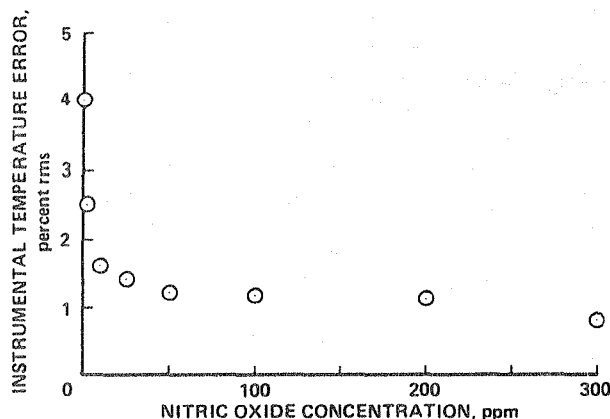


Fig. 5 Instrumental temperature error as a function of nitric oxide concentration, using single-photon excitation in a nonflowing cell at ambient temperature:  $P = 0.5$  atm.

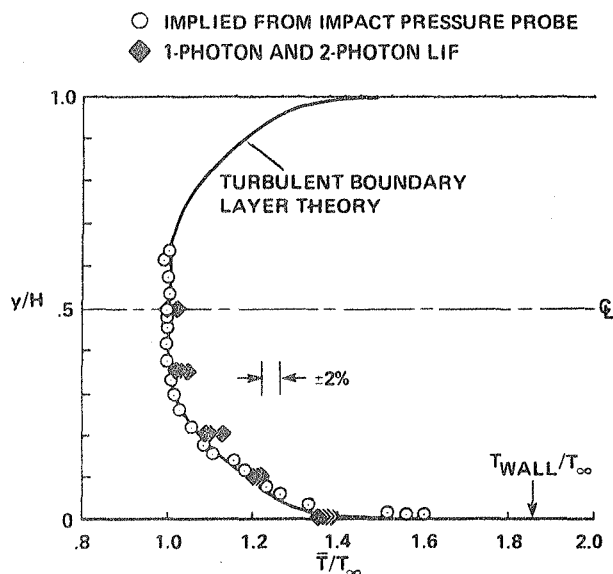


Fig. 6 Average temperature distribution through the boundary layer: channel height  $H = 32.5$  mm;  $M_\infty = 2$ ;  $T_t = 295$  K;  $T_\infty = 158$  K.

two-photon data are presented together and are shown by the solid symbols. They represent averages accumulated during 13-sec runs, with account taken of the declining stagnation temperature that is characteristic of blowdown flow facilities. The values plotted are the corresponding average temperatures after 2 sec from the start of the run. The data-acquisition rate was limited by the digitizers to 5 Hz, corresponding to 65 temperature determinations per run. The open symbols are temperatures implied from a pitot probe survey at the same conditions, using the standard one-dimensional equations derived for isentropic compressible flow<sup>6</sup> and assuming that the total temperature and static pressure are constant through the boundary layer. The solid theoretical curve is a solution of the compressible, turbulent, boundary-layer equations using a two-layer algebraic eddy-viscosity model.<sup>7</sup> Average temperatures

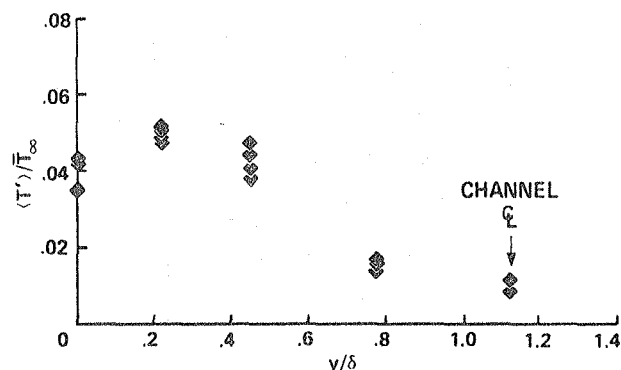


Fig. 7 Distribution of rms temperature fluctuations in the boundary layer using single-photon LIF;  $y/\delta$  is the location perpendicular to the wall normalized to the boundary-layer thickness. Gas mixture, 100 ppm NO;  $T_\infty = 158$  (Mach 2);  $\delta = 1.4$  cm.

determined using either one- or two-photon excitation are in agreement with one another and both agree with the pitot probe results to within  $\pm 2\%$ .

Figure 7 depicts the rms magnitudes of the temperature fluctuations owing to turbulence, obtained by single-photon LIF for an NO concentration of 100 ppm. The total rms deviations have been corrected by removing the average instrumental noise of  $\approx 1\%$  determined from the static calibration runs, thus leaving only the fluctuating temperature component resulting from the local flow conditions. Run-to-run variations of the turbulence level determined at the same location in the boundary layer may be due in part to statistical uncertainties resulting from the limited number of data samples taken during a given wind-tunnel run.

### Conclusion

Quantitative nonintrusive measurements of fluctuating temperatures using laser-induced fluorescence have been made in a simple, well-characterized, Mach 2, turbulent boundary-layer flow, seeded with 100-300 ppm of NO. Results obtained using both one-photon and two-photon NO  $\gamma(0,0)$  rotational line excitation agree with average temperature profiles deduced from pitot-probe surveys to within 2%. The method using two-photon LIF has been shown to be much less sensitive for instantaneous measurements than the one-photon method, a result of optical Stark broadening caused by the high laser field intensities needed for the two-photon measurements. The application of one-photon LIF in this study has demonstrated the capability for directly measuring turbulent fluctuations of temperature as small as 1% of the average local value. Additionally, the one-photon technique remains fairly sensitive at much lower NO concentrations, and could be effectively implemented in larger scale facilities where lower seeding levels are more desirable.

Work in progress in our laboratory indicates that the present method can most likely be extended to include simultaneous density measurements using an off-resonance excitation approach similar to that described for flow studies using iodine fluorescence.<sup>8</sup> This refinement would allow

simultaneous measurements of temperature and density, thus providing nonintrusive pressure measurements.

#### Acknowledgments

The authors are grateful to D. J. Monson and P. Logan for providing the pitot tube measurements and boundary-layer calculations represented in Fig. 6.

#### References

<sup>1</sup>Peterson, C. W., "A Survey of the Utilitarian Aspects of Advanced Flowfield Diagnostic Techniques," AIAA Journal, Vol. 17, Dec. 1979, pp. 1352-1360.

<sup>2</sup>Lederman, S. and Sacks, S., "Laser Diagnostics for Flowfields, Combustion, and MHD Applications," AIAA Journal, Vol. 22, Feb. 1984, pp. 161-173.

<sup>3</sup>McKenzie, R. L. and Gross, K. P., "Two-Photon Excitation of Nitric Oxide Fluorescence as a Temperature Indicator in Unsteady Gasdynamic Processes," Applied Optics, Vol. 20, 1981, p. 2153.

<sup>4</sup>Gross, K. P. and McKenzie, R. L., "Single-Pulse Gas Thermometry at Low Temperatures Using Two-Photon Laser-Induced Fluorescence in NO-N<sub>2</sub> Mixtures," Optics Letters, Vol. 8, 1983, p. 368.

<sup>5</sup>Huo, W. M., Gross, K. P., and McKenzie, R. L., "Optical Stark Effect in the Two-Photon Spectrum of NO," to be submitted to Physical Review Letters.

<sup>6</sup>"Equations, Tables, and Charts for Compressible Flow," NACA-1135, 1953.

<sup>7</sup>"Boundary Layer Integral Matrix Procedure, Version C (BLIMPC)," Aerotherm Report No. UM-70-20, June 22, 1970.

<sup>8</sup>McDaniel, J. C., Baganoff, D., and Byer, R. L., "Density Measurement in Compressible Flows Using Off-Resonant Laser-Induced Fluorescence," Physics of Fluids, Vol. 25, 1982, p. 1105.



1. Report No. NASA TM-85949	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle OPTICAL MEASUREMENTS OF FLUCTUATING TEMPERATURES IN A SUPERSONIC TURBULENT FLOW USING ONE- AND TWO-PHOTON, LASER-INDUCED FLUORESCENCE		5. Report Date May 1984	
		6. Performing Organization Code	
7. Author(s) K. P. Gross (Polyatomics Research Institute, 1101 San Antonio Road, Suite 420, Mountain View, CA 94043) and R. L. McKenzie		8. Performing Organization Report No. A-9724	
		10. Work Unit No. T-6482	
9. Performing Organization Name and Address Ames Research Center Moffett Field, CA 94035		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code 506-54-11-01-00	
15. Supplementary Notes Point of Contact: K. P. Gross, Ames Research Center, MS 229-1, Moffett Field, CA 94035 (415) 965-6255 or FTS 448-6255			
16. Abstract  A laser-induced fluorescence technique has been developed that provides a practical means of nonintrusively measuring the instantaneous temperatures in low-temperature turbulent flows. The capabilities of the method are reviewed, and its application to a simple, two-dimensional, turbulent boundary-layer flow at Mach 2 is reported. Measurements of the average temperature distribution through the boundary layer and the magnitudes of temperature fluctuations about their average values are presented.			
17. Key Words (Suggested by Author(s)) Flow diagnostics Temperature measurement Laser-induced fluorescence Nitric oxide fluorescence		18. Distribution Statement  Unlimited  Subject Category - 35	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 9	22. Price* A02

**End of Document**