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# Fiber–Optic Probe for Laser-Induced Fluorescence Measurements of the Fuel–Air Distribution in Gas-Turbine Combustors

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**A fiber–optic probe has been developed for spatially and temporally resolved measurements of the equivalence ratio in actual gas-turbine combustors. The measurement is based on laser-induced fluorescence, where acetone is used as a fluorescence seed. The effects of acetone concentration, temperature, and pressure on the fluorescence signal have been characterized in a steady flow test cell at temperatures (up to 400°C) and pressures (up to 12 atm) representative of real-gas-turbine combustors. The capabilities of the fiber-optic probe have been demonstrated by making measurements in a turbulent axisymmetric airjet. Under typical measurement conditions it has been shown that the mean and rms fluctuation of the equivalence ratio can be determined with an accuracy of better than ±5%.**

## Introduction

A MAJOR concern in the development of gas-turbine combustors for both land-based and aircraft applications is achieving the ultralow $NO_x$ emissions required to meet current and future emissions regulations. A number of ultralow $NO_x$ combustor concepts are currently under study, including lean premixed (LP) combustors, lean direct-injection combustors, rich burn-quick quench-lean burn combustors, and catalytic combustors. A key factor affecting both the emissions and performance characteristics of all these combustor concepts is fuel–air mixing. For example, incomplete fuel–air mixing in an LP combustor results in increased $NO_x$ emissions[1–5] and reduced combustion stability.[4,5]

To determine the degree to which fuel–air mixing is a limiting factor in achieving the desired emissions and performance characteristics in a gas-turbine combustor, it is essential that the actual fuel–air distribution be measured. Traditionally, this information has been obtained using gas-sampling probes, however, such an approach is not capable of resolving temporal fluctuations in the local equivalence ratio. More promising approaches involve the use of laser-based measurement techniques. Fric[3] and McMurray[6] used $NO_2$ laser-induced fluorescence to quantify unmixedness in laboratory-scale, atmospheric pressure dump combustors. This involved using $NO_2$ gas as a seed in a fuel stream and probing with an argon–ion laser. In addition to the fact that $NO_2$ is extremely toxic, this approach is limited by fluorescence quenching at high pressures.[7] More recently, Mongia et al.[8] used a fiber–optic probe based on methane absorption of the 3.39-μm output of an He–Ne laser to measure the extent of turbulent mixing in a laboratory scale, atmospheric pressure, piloted coaxial burner. This approach has the advantage that it is not necessary to add seed to the fuel, however, it is limited by the fact that the probe disturbs the flow in the region where the measurement is made.

Because optical access to an actual gas-turbine combustor using a conventional window and lens combination is very difficult to achieve, a fiber–optic probe that uses optical fibers as light guides is the most promising method for implementation of laser-based measurements in a real combustor. The fiber–optic equivalence ratio probe reported in this paper is based on laser-induced fluorescence and is capable of space- and time-resolved, quantitative measurements of the fuel–air equivalence ratio in the combustion chamber of an operating combustor.

## Description of Fiber–Optic Probe

A schematic drawing of the fiber–optic equivalence ratio probe is shown in Fig. 1. The overall diameter of the probe is 5/8 in. (15.9 mm), whereas the length can be made to accommodate a variety of applications, e.g., lengths as long as 4 ft (1.2 m) have been made to date. The probe consists of a stainless-steel, water-cooled jacket, inside of which are mounted two fused silica optical fibers, one for transmitting the laser beam and the other for transmitting the collected fluorescence signal. Figure 2 shows the tip of the probe, which houses mirrors and lenses for directing and focusing the laser beam out of the side of the probe tip and for collecting and focusing the fluorescence signal. The measurement volume, which is approximately 1 mm in diameter and 3 mm in length, is located 1 in. (25 mm) from the side of the probe and faces upstream, preventing the presence of the probe from affecting the mixing characteristics at the measurement location.

## Fluorescence Technique

Laser-induced fluorescence (LIF) has been successfully used in a variety of combustion applications for characterizing fuel–air mixing,[3–7,9,10] where the fluorescence of the fuel, or a fluorescence seed that is added to the fuel, is employed. Using a fluorescence seed has the advantage that the concentration of the fluorescence species can be controlled and that the fluorescence seed can be selected for its optimum physical and spectroscopic properties, making quantitative equivalence ratio measurements possible. The main disadvantages of using a fluorescence seed are the added complexity and expense.

A number of species have been employed as fluorescence seeds for fuel–air mixing studies. The fluorescence characteristics of various molecules that could be used as fluorescence seeds have been extensively reviewed.[11–14] A number of factors must be considered when selecting the fluorescence seed, including its boiling point, autoignition temperature, absorption and fluorescence characteristics, mass diffusion coeffi-

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**Table 1 Fluorescent characteristics of some aliphatic compounds**

| Compound | Boiling point, °C | Autoignition temperature, °C | Vapor pressure, torr @ 20°C | Absorption band, nm–nm | $\sigma_m$[a] $\times 10^{-20}$ cm$^2$ | $\phi$,[b] % | Fluorescence band, nm–nm | $\tau$,[c] ns | Cost[d] $/l |
|---|---|---|---|---|---|---|---|---|---|
| Acetone | 56 | 465 | 184 | 225–320 | 4.7@275 nm | 0.2 | 350–550 | 4 | 10 |
| Biacetyl | 88 | 285 | 40 | 340–470 | 8@417 nm | 0.25 | 420–520 | 15 | 130 |
| Acetaldehyde | 21 | 175 | 750 | 250–340 | 4.6@290 nm | 0.15 | 350–480 | 4 | 90 |
| 3-Pentanone | 102 | 451 | 20 | 220–320 | 5.8@280 nm | N/A | 330–600 | N/A | 50 |

[a]Maximum absorption cross section. [b]Fluorescence efficiency. [c]Fluorescence lifetime. [d]Approximate price quoted by Aldrich Chemical Co., Inc., for HPLC grade.

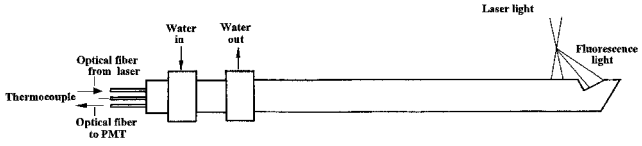


**Fig. 1 Schematic of fiber-optic probe.**

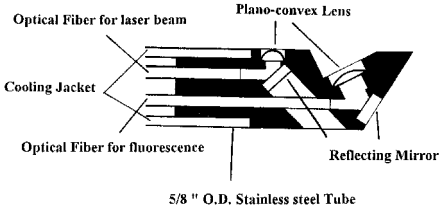


**Fig. 2 Detailed view of probe tip.**

cient, cost, and toxicity. The fuel characteristics must also be considered. In the case of a multicomponent liquid fuel, the different boiling points of the fuel components must be considered. One approach is to select a fluorescence seed with a boiling point that is close to the midpoint of the boiling range of the multicomponent fuel. To date, the probe reported herein has been used in gaseous-fueled, i.e., methane and natural gas-fueled combustors, and acetone has been used as the fluorescence seed. The relevant characteristics of acetone are compared to those of a number of other widely fluorescence seeds in Table 1. The main advantages of acetone are that it is easily vaporized, it has a high autoignition temperature, and it is relatively inexpensive. In addition, the coefficient of vapor phase mass diffusion in air for these fluorescence seeds are compared to that of methane in Table 2, showing that there is as large as a factor of 3 difference between the molecular mass diffusion rates for the various seeds compared to that of methane. However, in a gas-turbine combustor, the mixing between fuel and air is dominated by turbulent mixing, not by molecular diffusion; therefore, it can be assumed that the seed mixes with the air in the same way as the fuel, as long as the fuel and seed are initially well mixed.

## Experimental Setup

Excitation of acetone is readily accomplished with the fourth harmonic of a pulsed Nd:YAG laser (266 nm). This laser provides excellent temporal resolution, i.e., less than 10 ns; however, the measurement rate is limited by its relatively low pulse rate, i.e., of the order of 10–100 Hz. A nominal laser pulse energy at the measurement volume of 0.2 mJ is used. The overall transmission efficiency of the probe optics is 25% and, therefore, a laser energy of ~1 mJ per pulse at 266 nm is required. This is provided by a small mini-YAG laser (Continuum Minilite), which significantly enhances the portability of the probe system for field use. The laser is operated at 10 Hz, the beam diameter is 3 mm, the beam divergence is 3 mrad, and the pulse duration is 5 ns. Before the laser beam is launched into the optical fiber, a small fraction of the beam is reflected by a quartz plate onto a photodiode to measure the laser pulse energy. This measurement is used to normalize the fluorescence signal and thereby account for pulse-to-pulse variations in the laser pulse energy.

**Table 2 Molecular coefficients (cm$^2$/s) of vapor phase mass diffusion in air at 1 atm[15]**

| Compound | @25°C | @400°C |
|---|---|---|
| Acetone | 0.1049 | 0.4741 |
| Biacetyl | 0.0845 | 0.3918 |
| Acetaldehyde | 0.1445 | 0.5871 |
| 3-Pentanone | 0.0810 | 0.3723 |
| Methane | 0.2240 | 0.9411 |

The collected fluorescence signal is transmitted by optical fiber from the probe tip to a photomultiplier tube (PMT), in front of which are mounted a long-pass filter (WG 345) and a 40-nm-wide bandpass filter centered at 400 nm to spectrally isolate the acetone fluorescence and reject unwanted elastic scattering at the laser wavelength. To increase the linearity and the dynamic range of the PMT for pulsed operation, a so-called tapered bleeder circuit is employed, which improves the linearity of the PMT by nearly a factor of 10 compared to the normal equally divided circuit.

The signals from the photodiode and PMT are passed to a boxcar integrator and the resulting outputs are digitized with 12-bit resolution using a PCMCIA (Personal Computer Memory Card International Association) data acquisition card installed in a notebook computer.

## Calibration of Fiber–Optic Probe

The effects of acetone concentration, temperature, and pressure on the detected fluorescence signal were characterized using a stainless-steel test cell, which is capable of operation at pressures up to 12 atm and temperatures up to 400°C. Liquid acetone is metered and introduced through a 1/16-in.-diam tube into a small tee where it vaporizes and mixes with a metered and preheated airstream. After passing through a long 1/4-in.-diam tube ($L/D$ = 200), the mixture of vaporized acetone and air is introduced into the test cell. Only at the lowest acetone flow rates (typically 0.15 cc/min) was the acetone seeding rate observed to be unsteady.

Figure 3 demonstrates the linearity of the acetone fluorescence signal over a range of acetone concentrations from 0.5 to 3.0 vol % in air at 1 atm and 60°C. Each datum point corresponds to the mean fluorescence signal and the error bars represent the standard deviation (or rms fluctuation) calculated from 600 individual measurements. Possible sources for the measured rms fluctuation are unsteadiness associated with acetone seeding and signal shot noise, etc. The minimum detectable acetone concentration depends on many factors such as laser power, the launching efficiency of the laser beam into the optical fiber, the length of the optical fiber, and the PMT voltage. In the test cell, the background noise is very low; however, because of fluctuation in the acetone seeding rate, the minimum detectable volumetric concentration of acetone in air was about 0.05% (500 ppm) at atmospheric pressure. Using this as an estimate of the minimum detection limit in an actual measurement, an acetone concentration of 1% in the fuel would be required to measure equivalence ratios as low

as 0.1 in a methane-fueled combustor. Obviously, increased background noise would require larger seed concentrations, whereas increased combustor pressure would allow the use of lower seed concentrations. A limited number of tests were also done using acetone seed in methane–air mixtures to investigate the possibility of quenching of the acetone fluorescence by methane. These tests showed no evidence of such quenching.

An important issue with respect to quantifying any LIF measurement is the effect of collisional quenching, which, in general, varies with temperature, pressure, and gas composition. Quenching reduces the fluorescence intensity and introduces significant uncertainty, i.e., as large as ±100%, in the quantitative interpretation of the fluorescence signal. Fortunately, collisional quenching is known to be relatively negligible for the dominant de-excitation path of excited state acetone.[14] Therefore, the fluorescence quantum yield is independent of molecular collisions and, as a result, independent of gas temperature, pressure, and composition. In the case of acetone, however, dissociation into methyl and acetyl radicals, which is temperature dependent,[16] must be considered since this can also reduce the fluorescence signal strength. Figure 4 shows the effect of temperature on the acetone fluorescence intensity. Again, the indicated fluorescence data are averages over 600 laser pulses. In this case the probe temperature was maintained at 50°C. Since the measurements were made at a fixed volume percent of acetone, the fluorescence intensity, normalized by the laser power and divided by the gas density, is plotted vs the gas temperature. These results indicate that at temperatures above ~300°C dissociation effects begin to become important and, as a result, temperature variations can result in acetone fluorescence intensity variations that could be misinterpreted as variations in the equivalence ratio. For example, a ±30°C temperature variation about a mean temperature of 370°C will result in an apparent ±8% variation in equivalence ratio.

Figure 5 shows the effect of pressure on the acetone fluorescence intensity over a range of pressures from 1 to 12 atm, at a temperature of 60°C. Again, the indicated fluorescence data are averages over 600 laser pulses. The fluorescence intensity is shown to increase linearly with pressure, indicating that pressure has no effect on the fluorescence intensity as a result of quenching or dissociation. In fact, this result indicates that measurements at elevated pressures are advantageous because of the increased fluorescence signal strength. The maximum pressure tested was limited by the maximum operating pressure of the test cell; however, the fluorescence signal can be extrapolated to higher pressures.

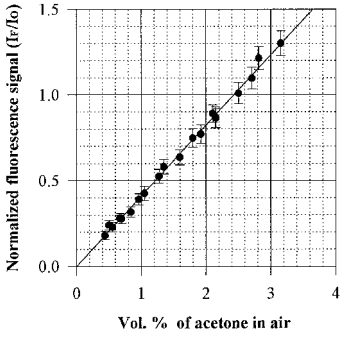


**Fig. 3 Normalized fluorescence signal vs volumetric concentration of acetone in air (at 1 atm and 60°C).**

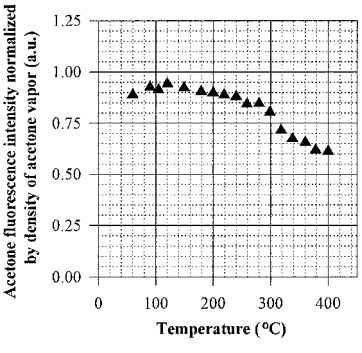


**Fig. 4 Effect of temperature on acetone fluorescence.**

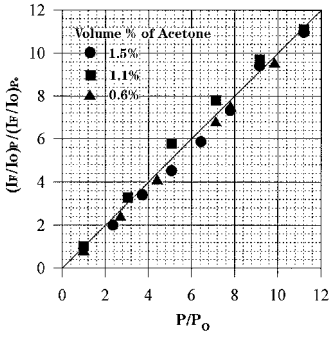


**Fig. 5 Effect of pressure on acetone fluorescence.**

## Demonstration of Fiber–Optic Probe

To demonstrate the capabilities of the fiber–optic equivalence ratio probe, measurements were made in an acetone-

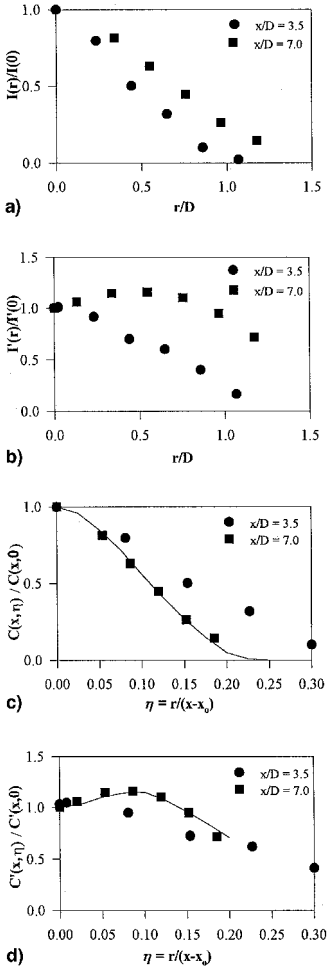


**Fig. 6 a) and b) Normalized radial mean concentration [$I(r)/I(0)$] profile and rms concentration fluctuation [$I'(r)/I'(0)$] profiles at $x/D = 3.5$ and 7.0; c) and d) comparison of the measured mean and fluctuation concentration profiles with the similarity results of Dowling and Dimotakis.[17]**

seeded turbulent axisymmetric airjet. The acetone is sprayed into a mixing tube where it is vaporized and mixed with preheated air. The air–acetone vapor mixture runs through a long tube ($L/D$ = 200) to ensure complete mixing and exits horizontally from a 4.8-mm-i.d. tube at a velocity of 150 m/s ($Re_D = 3.7 \times 10^4$). The main jet was surrounded by a low-speed (2–7 m/s) annular coflow of air, which is confined within a 7.5-cm-diam tube. The temperatures of the main jet and coflow were 60°C.

Figure 6 shows radial measurements at two different axial locations, 3.5 and 7.0$D$ downstream of the tube exit. Each datum point is an average of 1000 samples, and the fluorescence intensity was normalized by the laser pulse energy and mean centerline fluorescence intensity. The volumetric concentration of acetone in the main jet was maintained at 2%. Qualitatively, the results are as expected, i.e., the normalized mean concentration profiles have Gaussian shapes and the half-maximum width of the jet increases (from 3.8 to 5.6 mm) as axial downstream distance increases from 3.5 to 7.0$D$. The measurements are also compared to the results of Dowling and Dimotakis[17] in Figs. 6c and 6d. The measured mean and rms fluctuation concentrations were fitted to Dowling and Dimotakis'[17] similarity profiles using the parameter $k$ = 5.0, the momentum diameter $d^* = D$, and the virtual diameter $x_0 = 0.5D$. The agreement between the mean and rms fluctuation measurements and their similarity profiles is within ±5% at the axial location of 7.0$D$. The disagreement observed at 3.5$D$ is expected since the self-similarity of the jet is only valid in the far field.

Recently, the fiber–optic equivalence ratio probe has also been successfully employed to measure the spatial and temporal fuel–air distributions in a number of full-scale, single-nozzle combustor facilities at pressures up to 10 atm and inlet temperatures up to 400°C, both with and without combustion.[18,19] The results obtained in these tests have been consistent with the measurement capabilities presented in this paper.

## Conclusions

A fiber–optic probe for laser-induced fluorescence measurements of the fuel–air distribution in gas-turbine combustors has been developed and calibrated over temperature and pressure conditions representative of real-gas-turbine combustors. Under typical measurement conditions in a turbulent axisymmetric airjet, it has been shown that the mean and rms fluctuation of the equivalence ratio can be determined with an accuracy of better than ±5% for local fuel–air equivalence ratio of 0.1 and above.

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