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Combustion and Flame 132 (2003) 272–274  
Brief communication

Combustion  
and Flame

# Two-photon laser-induced fluorescence measurement of CO in turbulent non-premixed bluff body flames

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Received 23 April 2002; received in revised form 27 June 2002; accepted 7 July 2002

## Abstract

Detailed measurements of reactive and passive scalars in axisymmetric bluff-body flames of CH<sub>4</sub>/H<sub>2</sub>, CH<sub>4</sub>/air, and CO/H<sub>2</sub> have been reported in the past [1] and have been used in several studies directed at developing and validating turbulent combustion models [2–5]. Comparisons of measured and modeled results for flames with CH<sub>4</sub>/H<sub>2</sub> as fuel have shown significant disagreement in the mass fractions of CO, with the Raman scattering measurements of [CO] being much higher than the modeling calculations. Previously published data [1] were collected using the Raman scattering technique for all major species including CO. Raman scattering measurements of [CO] in methane flames suffer from laser-excited interference from higher hydrocarbons formed on the fuel-rich side of the reaction zone. It is well established [6–8] that measurements of [CO] based on two-photon laser-induced fluorescence (TPLIF) can provide much better accuracy than those based on Raman scattering in methane and natural gas flames. © 2003 The Combustion Institute. All rights reserved.

**Keywords:** Bluff body; CO; LIF; Raman; Flame

## 1. Introduction

This brief communication presents new results for [CO] in three bluff body flames with CH<sub>4</sub>/H<sub>2</sub> as fuel. These new results are based on TPLIF measurements acquired as part of the original simultaneous Raman/Rayleigh/LIF experiment [1], but were not processed at that time because the methods of analysis were still in development. The importance of these bluff body flames for validating models has motivated the present work to analyze and present the original TPLIF measurements of [CO]. The complete data sets for the bluff

body flames of CH<sub>4</sub>/H<sub>2</sub>, including these new results, are available on the Web [9].

## 2. Experimental

The setup for simultaneous Raman/Rayleigh/LIF measurements, including TPLIF measurements of [CO] as applied in this study, has been described extensively [6–8,10,11]. A brief summary of the TPLIF method is given below. A Nd:YAG-pumped dye laser with crystals for doubling and mixing was used to excite two-photon LIF of the  $B^1\Sigma^+$  ( $v' = 0$ ) ←  $X^1\Sigma^+$  ( $v'' = 0$ ) band with  $\sim 700 \mu\text{J/pulse}$  at 230.1 nm. The beam waist diameter was less than 0.3 mm. This level of laser irradiance was sufficient to promote photo-ionization as the dominant loss mechanism from the CO excited state, such that the measured exponent for the dependence of fluorescence

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signal on laser power was near unity, and the influence of collisional quenching on the fluorescence yield was suppressed [10,11]. The Nd:YAG laser was seeded to reduce energy fluctuations to less than 4% at 230.1 nm. A cell with a mixture of CO-He-N<sub>2</sub> (5%–45%–50%) at room temperature was used to monitor the laser wavelength during all measurements. The CO TPLIF signal was then linearly normalized with measured laser irradiance on a shot-to-shot basis. The CO-LIF emission from the  $B^1\Sigma^+$  ( $v' = 0$ )  $\rightarrow$   $A^1\Pi^+$  ( $v'' = 1$ ) band was collected using a PMT with two bandpass filters (25 and 10 nm bandwidths) centered at 484 nm. Calibration of the CO-LIF signal was done in a similar way to that of the Raman signal [6], using flat flames and heated flows with known [CO] over a wide temperature range (300–2100K) to generate the polynomial calibration curve. Data processing included a correction for interference due to photodissociation of CO<sub>2</sub> [11]. Uncertainty in the averaged CO-LIF results presented here is believed to be 10 to 20%. This includes calibration drift and uncertainty in the interpolated calibration curve.

### 3. Results and discussion

Data collected for three flames with a fuel of H<sub>2</sub> and CH<sub>4</sub> (1:1 by volume) are considered here, and the [CO] from Raman scattering and TPLIF are compared. These flames have relatively low [CO] and the Raman signal from CO suffers most from hydrocarbon fluorescence interference, compared to the other flames in the original study [1]. Three flames have bulk fuel velocities at the jet exit of  $U_j = 118$  m/s for case HM1 in the database [9],  $U_j = 178$  m/s for case HM2, and  $U_j = 214$  m/s for case HM3. The air co-flow was fixed at 40 m/s. Other parameters of the burner and experimental conditions are described fully in [1,9].

Figure 1 presents measured [CO] (in mass %) plotted against the mixture fraction for the HM1 flame at three axial locations. The mixture fraction was calculated using Bilger's formula [12], which preserves the stoichiometric value of mixture fraction in the presence of differential molecular diffusion. The left column shows plots of data measured using the Raman technique, while the right column shows plots of data measured using the TPLIF technique. Scatter plots at three axial locations downstream of the bluff-body burner are compared with laminar flame calculations with and without differential diffusion. The computed laminar flames have a moderate stretch rate of  $a = 100$  s<sup>-1</sup>. The TPLIF measurements of [CO] show less scatter and are clearly less affected by fluorescence interferences than the Ra-

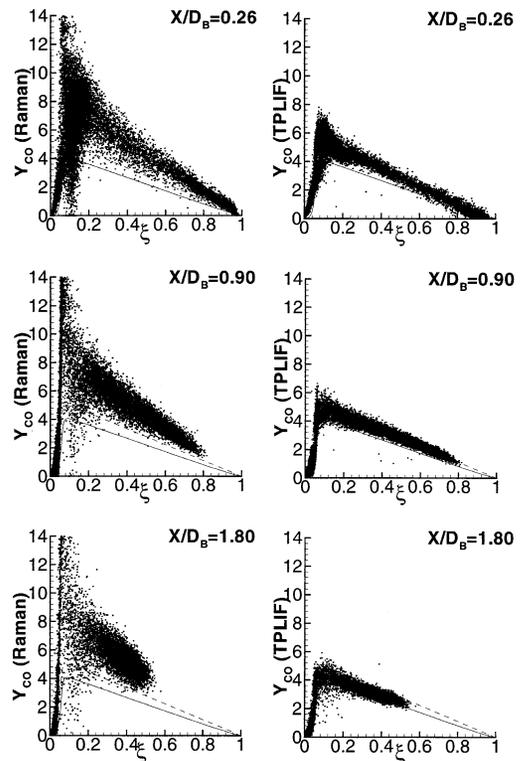


Fig. 1. Scatter plots of  $Y_{CO}$ , measured mass fractions of CO, plotted against  $\xi$ , the mixture fraction for the turbulent non-premixed flame HM1 of CH<sub>4</sub>/H<sub>2</sub> (1:1 by volume) stabilized on a bluff-body. The plots in the left column were measured using the Raman technique; those in the right column were measured using the TPLIF technique. The plots are for  $x/D_B = 0.26, 0.9,$  and  $1.8$ , where  $x$  is axial distance from the burner and  $D_B = 50$  mm, is the bluff-body diameter. The lines represent laminar flame calculations at a strain rate of  $a = 100$  s<sup>-1</sup> for the standard treatment of multicomponent transport (solid line) and the case of equal diffusivities, where  $Le = 1.0$  (dashed line).

man scattering measurements. The interference problem in the Raman measurements is most apparent just to the fuel-rich side of stoichiometric mixture fraction, where fluorescence interference signals are highest. The TPLIF results in Fig. 1 are considered to be more accurate than the Raman results. They are also more consistent with the laminar calculations and with modeled results for these turbulent flames [5].

Figure 2 shows radial profiles of Favre averaged mass fractions of CO, in percent, at four axial locations. At location  $x/D_B = 0.26$ , [CO] in the recirculation zone is almost uniform with a value of  $\sim 5\%$  for flames HM1 and HM2. These two flames have the reaction zone at the outside envelope of the outer vortex. It is notable that the average temperature (not shown) at this location for flame HM2 is 300 K lower

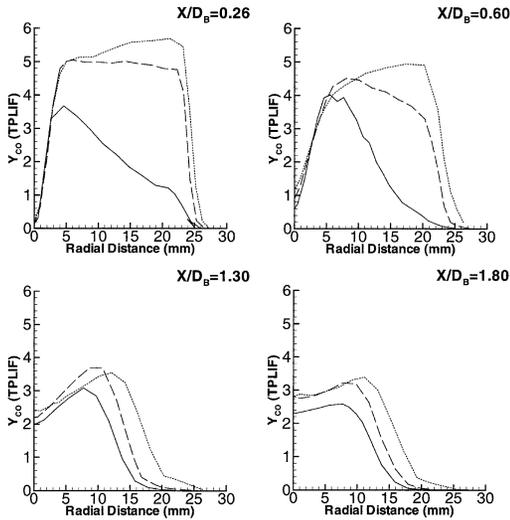


Fig. 2. Radial profiles of the measured mean mass fractions (using TPLIF) of CO (in %) for three turbulent non-premixed flames of  $\text{CH}_4/\text{H}_2$  (1/1 by vol.) stabilized on a bluff-body: HM1 (dotted line), HM2 (dashed line) and HM3 (solid line). Each plot corresponds to a different axial location as indicated on the plots.

than flame HM1. Flame HM3 has the reaction zone closer to the inner vortex with a leaner recirculation zone, and the [CO] peaks at  $\sim 4$  mm from the centerline with a maximum mean mass fraction of  $\sim 3\%$ .

For location  $x/D_B = 0.6$  similar peak values are found, albeit with wider distributions in flames HM1 and HM2. The radial distribution and peak values are mainly a property of the flow as most of the reaction happens in the outer edge. For locations  $x/D_B = 1.3$  and  $1.8$ , which are outside the recirculation zone, similar profiles were found for flames HM1 and HM2, while the peak [CO] is  $\sim 20\%$  lower for flame HM3.

In summary, newly analyzed results for [CO], based upon two-photon laser-induced fluorescence measurements in three bluff body flames of  $\text{CH}_4/\text{H}_2$  as fuel, have been compared with the originally reported Raman scattering results. Results from the fluorescence technique are considered to be more

accurate and are recommended for use in any future comparisons with modeling calculations.

### Acknowledgment

The authors acknowledge the ARC for financial support and CRF at Sandia National Laboratories for access to their laboratories and their support during the experiments. Work at Sandia was supported by the US Department of Energy office of Basic Energy Sciences.

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