Simultaneous Optical Measurement of Soot Volume Fraction and Temperature

M.Y. Choi, A. Hamins and T. Kashiwagi
Building And Fire Research Laboratory
National Institute Of Standards And Technology
Gaithersburg, MD 20899

INTRODUCTION

Radiative heat transfer processes in large fires govern the burning rate, the flame spread rate and the potential for fire hazards. These processes are controlled by the detailed structure of the fire, primarily the temperature and soot distributions. In an attempt to characterize the radiative heat transfer, Gore and coworkers developed an optical probing technique [Sivathanu *et al.*, 1991; Klassen *et al.*, 1992a, 1992b]. The technique utilizes a multi-line emission and absorption probe to simultaneously measure the temperature and soot volume fraction within a narrow region of a fire.

For the extinction measurements, the transmittance of light through the flame is related to the soot volume fraction (f_{va} is based on absorption) and the absorption coefficient (K_λ) along the radiation path, L (scattering is neglected):

$$\frac{I_\lambda}{I_{\lambda o}} = e^{-\frac{K_\lambda \cdot f_{va} \cdot L}{\lambda}}$$

where λ is the wavelength of the incident light ($I_{\lambda o}$).

The emission intensity is given by

$$I_\lambda = \frac{\int I_{b\lambda} F_\lambda \left(1 - e^{-\frac{K_\lambda \cdot f_{ve} \cdot L}{\lambda}}\right) d\lambda}{\int F_\lambda d\lambda}$$

where F_λ is the sensitivity characteristics of the emission detectors and $I_{b\lambda}$ is

$$I_{b\lambda} = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{k\lambda T}} - 1\right)}$$

Combustion Institute/Central and Eastern States Section. Combustion Fundamentals and Applications. Joint Technical Meeting. March 15-17, 1993, New Orleans, LA, 532-536 pp, 1993.

where h is Planck's constant, c is the speed of light and k is Boltzmann's constant. The temperature and soot volume fraction associated with the emission measurement (f_{ve}) are calculated by simultaneously solving the emission intensity equations associated with the two wavelengths at 900 and 1000 nm.

The calculated soot volume fractions and temperatures in conjunction with multi-ray heat transfer calculations can be used to predict the radiative heat transfer from the flame surface to the fuel surface and the surroundings [Klassen *et al.*, 1992a, 1992b].

In order to investigate the efficacy of this technique for measuring temperature and soot volume fraction distributions, a series of experiments were undertaken. A premixed flat flame burner was used to create a homogeneous high temperature environment. Under conditions of homogeneity, f_{ve} and f_{va} should be equal [Sivathanu *et al.*, 1991]. Thus, a rigorous test of the precision of the measurement can be accomplished.

EXPERIMENTAL TECHNIQUE

Figure 1 displays the schematic diagram of the experimental apparatus. It is similar to that described previously [Klassen *et al.*, 1992]. The absorption experiment uses a 632.8 nm helium neon laser. The emission information from the probe volume is collected at central wavelengths of 900 and 1000 nm with a bandwidth of 50 nm. The individual probe is an assembly of two concentric stainless steel tubes of 1/4" and 1/8" diameter. This assembly eliminated the effect of IR emission (caused by heating of the metal from the fire) of the probes during the sampling period which can compromise the emission measurements. In the current system, light signals are carried through a trifurcated fiber optic bundle which enables the translation of the probes throughout the fire.

RESULTS

Experiments were performed for pre-mixed ethylene/air flames burning in a 6 cm diameter water cooled McKenna burner. The probes were separated by 20 mm and were placed 25 mm above the burner surface. The fuel/air equivalence ratio was varied from 2.1 to 2.4. **Figure 2** displays the measured soot volume fractions and temperatures as a function of equivalence ratio for the ethylene/air flames. The mean values of f_{ve} and f_{va} are in good agreement with the values reported by Harris and Weiner [1983] for a similar experimental configuration. In their experiments, the soot volume fractions were measured using the scattering and extinction technique of D'Alessio *et al.* [1972]. Furthermore, their reported temperature for $\phi = 2.3$ is 1610 K which is in good agreement with our experimental value of 1603 K.

The difference between the f_{ve} and f_{va} values in **Figure 2** may have resulted from the non-uniform temperature distribution within the probe volume (f_{ve} is a measure of Planck-function weighted average of the soot particles, whereas, f_{va} is a measure of all the soot particles). To ensure a region of uniform temperature distribution, the probe was placed closer to the burner surface (7 mm). For these experiments, acetylene/air mixture ($\phi = 2.3$) was used to produce a luminous flame at this location. **Figure 3** displays the temperature, f_{ve} and f_{va} as a function of radial position from -10 mm to 10 mm. These experiments suggest that the temperature is relatively uniform within the distance bounded by the probes. However, f_{va} is greater than f_{ve} by nearly a factor of two. One possible explanation for this difference is the uncertainty in the absorption coefficient which can influence the calculation of f_{ve} and f_{va}. For example, a 10% uncertainty in the absorption coefficients will result in a 10% uncertainty for f_{ve} and f_{va}. The theory used by Dalzell and Sarofim [1969] assumes that the index of refraction is independent of temperature and soot structure formed by different fuels. The dispersion model used in their analysis was based on soot sampled from propane flames. Recent work of Sivathanu *et al.*, [1992] indicate negligible differences for the index of refraction of fuels such as methane, ethylene and propane. However, soot particles from acetylene or toluene flames possess larger primary and aggregate sizes and thus the use of the index of refraction for propane soot may lead to greater uncertainty.

Another possible explanation for the discrepancy between f_{ve} and f_{va} may be the relative importance of scattering by soot particles. Koylu and Faeth [1992] conclude that the scattering to absorption cross-section ratio can be as high as 0.55 to 0.6 for large acetylene soot agglomerates (produced in the over-fire region of turbulent diffusion flames) using a source wavelength 632.8 nm. By increasing the source wavelength (which decreases the optical dimension of soot), the relative importance of scattering to absorption can be reduced.

The acetylene/air flame experiments were repeated using infrared emitting diodes with a central wavelength of 940 nm as a radiating source. For these experiments, the relative importance of scattering compared to absorption should be reduced. The measured temperatures, f_{ve} and f_{va} are compared to the He-Ne extinction experiments in **Table I**.

TABLE I

Source Wavelength (nm)	**632.8**	**940**
Temperature (K)	**1682**	**1679**
f_{ve} (ppm)	**0.40**	**0.39**
f_{va} (ppm)	**0.72**	**0.60**

By using the infrared source, f_{va} was reduced from 0.72 to 0.60 (since the operating conditions were kept constant in both experiments, the temperature and f_{ve} did not change appreciably). However, the difference between f_{ve} and f_{va} remains large. Scattering experiments and experiments using longer wavelength infrared sources are being conducted to ascertain the degree of scattering under these conditions and its effects on the extinction results.

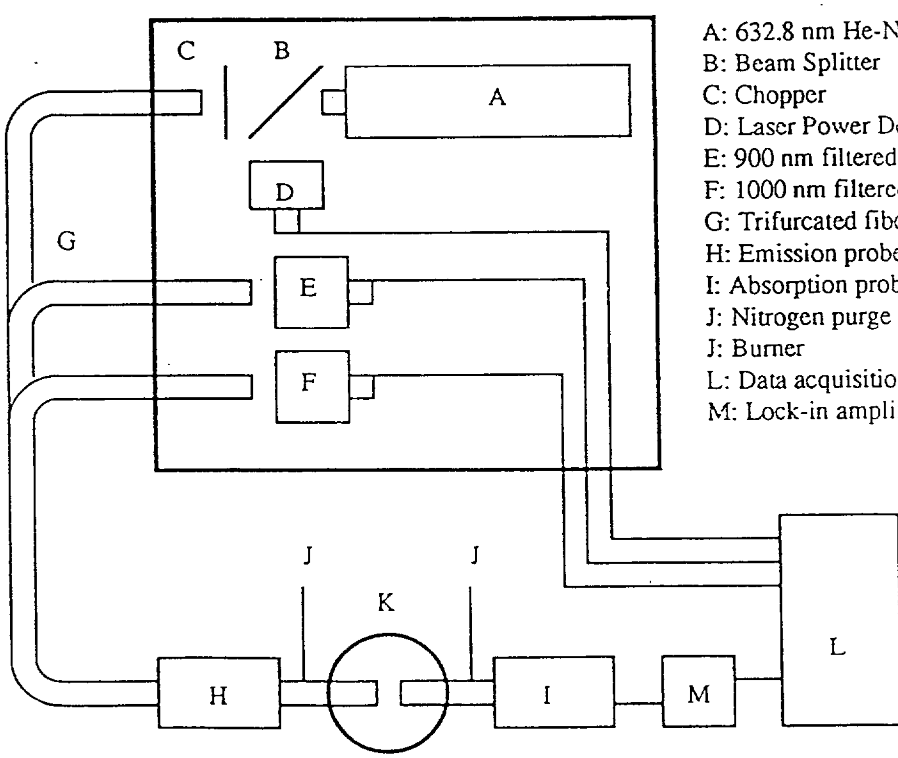
ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Professor J. Gore and Drs. M. Klassen and Y. Sivathanu of Purdue University.

REFERENCES

1. Sivathanu, Y.R., Gore, J.P. and Dolinar, J. (1991), "Transient Scalar Properties Of Strongly Radiating Jet Flames", Comb. Sci. Tech., **76**, p.45.
2. M. Klassen, J.P. Gore, A. Hamins and T. Kashiwagi (1992a), "Radiative Heat Feedback in a Toluene Pool Fire", Twenty-Fourth (International) Symposium on Combustion, The Combustion Institute, in press.
3. M. Klassen, Y.R. Sivathanu and J.P. Gore (1992b), "Simultaneous Emission Absorption Measurements in Toluene Pool Flames: Mean and RMS Properties, Combustion and Flame, in press.
4. Harris, S.J. and A.M. Weiner (1983), "Surface Growth of Soot Particles In Premixed Ethylene/Air Flames", Comb. Sci. Tech., **31**, p.156.
5. D'Alessio, A., Beretta, F. and Venitozzi. C. (1972), "Optical Investigations of Soot Forming Methane-Oxygen Flames", Comb. Sci. Tech, **5**, p. 263.
6. W.H. Dalzell and A.F. Sarofim (1969), "Optical Constants of Soot and Their Application to Radiative Heat Flux Calculations", J. Heat Transfer, **91**, p.100.
7. Koylu, U.O. and G.M. Faeth (1992), "Structure and Optical Properties of Overfire Soot In Buoyant Turbulent Diffusion Flames", Abstract presented at the Annual Conference On Fire Research, NIST.
8. Sivathanu, Y.R., Gore, J.P., Janssen, J.M. and Senser, D.W. (1992), "A Study of Insitu Specific Absorption Coefficients of Soot Particles in Laminar Flat Flames", ASME J. of Heat Transfer, Accepted for publication.

Figure 1



A: 632.8 nm He-Ne Laser
B: Beam Splitter
C: Chopper
D: Laser Power Detector
E: 900 nm filtered photodiode
F: 1000 nm filtered photodiode
G: Trifurcated fiber optic bundle.
H: Emission probe
I: Absorption probe
J: Nitrogen purge
J: Burner
L: Data acquisition system
M: Lock-in amplifier

Figure 2

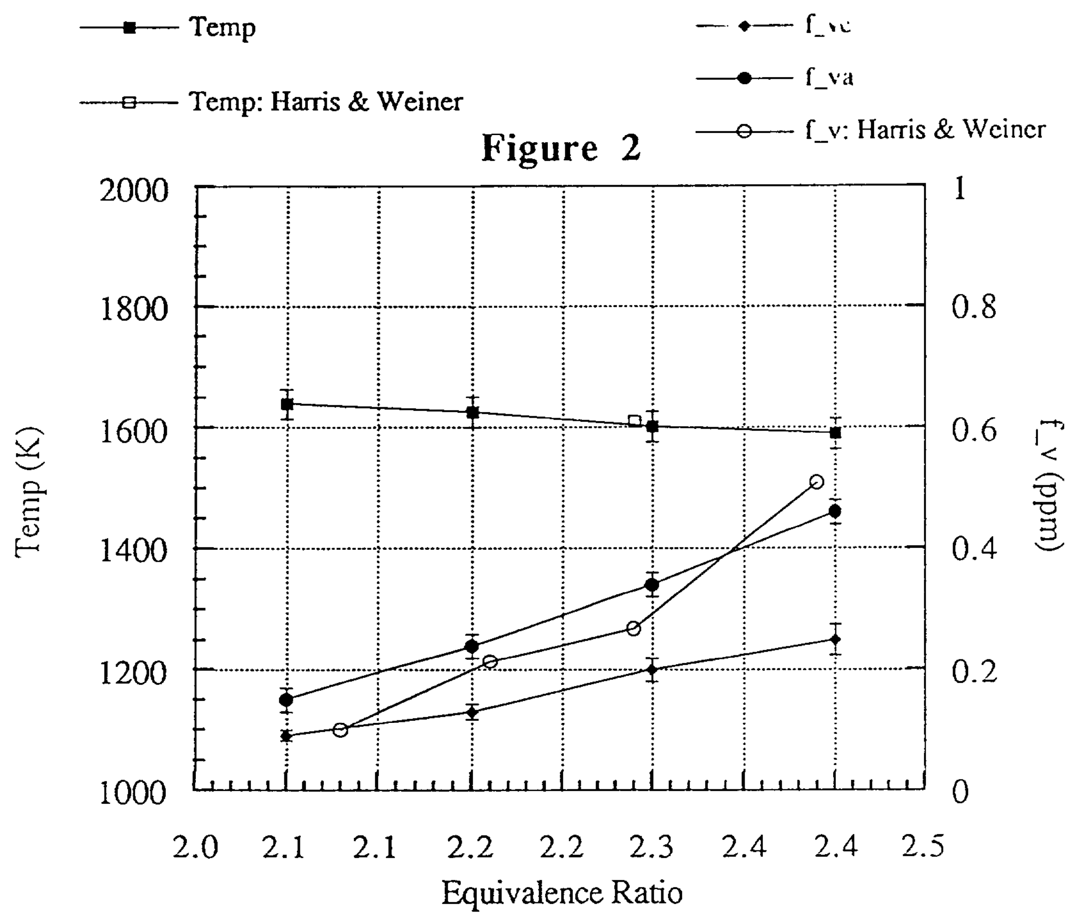


Figure 3