

## SIMULTANEOUS OPTICAL MEASUREMENT OF SOOT VOLUME FRACTION AND TEMPERATURE IN HEPTANE POOL FIRES

M.Y. Choi, A. Hamins, H. Rushmeier<sup>1</sup>, A. Hubbard and T. Kashiwagi  
BFRL, Nat'l Inst. Of Standards And Technology  
Gaithersburg, MD 20899

### INTRODUCTION

In large pool fires radiative heat transfer governs the burning and flame spread rates and therefore is a key factor in assessing potential fire hazards. The radiative heat feedback from the flame to the fuel surface is controlled by the temperature and soot distribution inside the fire. Early attempts at modeling this process involved several assumptions including the use of average flame emissivity, constant flame temperatures, absorption/emission coefficients as a function of height and effective flame shapes. Due to the turbulent nature of these fires, the use of mean radiative properties can lead to significant differences between the predicted and measured fuel burning rates. Markstein [1] investigated spatial and temporal variations of the emission intensity for pool fires and suggested the importance of turbulent fluctuations of temperatures and soot volume fractions on the heat transfer mechanism. Direct integration of the turbulent radiative heat transfer to the fuel surface requires the time-varying local temperature and emissivity distributions within the region between the fuel surface and the flame.

The primary motivation for this study is to understand the mechanisms governing the gasification and heat feedback rates to the fuel surface. The 3-line emission/absorption technique was used to measure the temperature and soot volume fractions ( $f_{va}$  based on absorption and  $f_{ve}$  based on emission) in pool fires burning heptane. The temporal and spatial results will be used to determine the radiative feedback to the surface and the burning rate using a reverse Monte Carlo method for comparisons with the measured values.

### POOL FIRE RESULTS

A detailed description of the experimental apparatus is given elsewhere [2,3]. The 3-line measurements were performed at various locations above the surface of a 10 cm burner (at  $X/D$  and  $R/D$  position, where  $X$  is height above the burner,  $R$  is the radial position with respect to the center of the burner and  $D$  is the burner diameter). Figure 1 displays the temperature,  $f_{va}$  and  $f_{ve}$  measurements at  $X/D=1.0$  and  $R/D=0.0$ . For the heptane fire, the average soot volume fractions are approximately an order of magnitude smaller than in toluene fires and the average temperatures are typically several hundred degrees higher than in the toluene flame [3]. There was concern that the reduced degree of sooting in the heptane fire (relative to toluene) would produce insufficient emission signals. However, the higher flame temperatures for heptane produced emission signals that were of comparable magnitude to the toluene fires. The differences in  $f_{va}$  and  $f_{ve}$  are attributed to the cold soot in the probe volume that does not contribute to the overall emission.

Due to the turbulent nature of pool fires, the emission data exhibited intermittent behavior. There are two possible reasons causing the intermittency in the emission data. At positions far removed from the fuel surface, the sporadic periods of low emission represent periods when the flame resides outside of the optical path length (this condition will be defined here as Case A). However, at positions near the burner surface, the low emission data are related to reduced  $T$  (defined as Case B).

In order to distinguish between Cases A and B, it was decided to use ionization gauges in conjunction with the emission measurements. The principle behind ionization gauges is simple: the current flow across the gap separating the ionization probes is associated with the presence of flame-generated ions. Thus, the gauge can be used as a simple on/off switch to determine the presence of the flame. Figure 2 displays the cross-correlation of ionization voltages measured by two separate ionization gauges as a function of horizontal distance between the two. The gauges were placed at  $X/D = 1.0$  and  $R/D = 0.0$ . As the horizontal distance between the two probes was decreased, the cross-correlation between the two signals increased. For higher separation distances, low cross-correlation was caused by the fact that the gauges were probing different parts of the flame. However, at a separation distance of 5 mm, independent measurements exhibited a high cross-

---

<sup>1</sup> Computing and Applied Mathematics Laboratory

correlation coefficient. Thus, placing the ionization gauge 5 mm from the optical path ensures high correlation with events occurring within the probe volume while causing minimal disturbances.

In a region that exhibited behavior that is characteristic of Case A ( $X/D = 3.0$ ,  $R/D = 0.0$ ), only 60% of the emission data had signals greater than the detection limit. Similarly, the percentage of data points with ionization voltage greater than the threshold value (the threshold value was chosen as  $V_{th} = V_{ion, Ave} + 3V_{ion, SD}$ ) was 62%. There was good correlation between the ionization and emission signals: i.e., for the high emission data points, simultaneous measurements of high ionization voltage signals occurred 70% of the time. Flamelets that are smaller than the path length can result in a detectable emission signal but not necessarily a detectable ionization voltage. However, in a region that exhibited behavior of Case B ( $X/D=0.2$ ,  $R/D = 0.0$ ), there was no recognizable correlation, i.e., the percentage of data points with emission greater than the detection limit was 41%, while 100% of the data points had ionization voltages greater than  $V_{th}$ .

In the heat transfer calculations, setting the temperature to 300K for all of the low emission data points may be valid for treating low emission periods corresponding to Case A, however the practice of artificially setting the temperature to 300K may not be appropriate for periods corresponding to Case B. Efforts are underway to formulate a more accurate method of determining the temperature for the low emission cases.

As mentioned in the introduction, the calculation of the radiative heat flux to the fuel surface requires spatial and temporal measurements of the temperature and soot volume fraction (i.e., instantaneous distributions of the temperature and soot volume fraction). However, in this work, the measurements at various locations were not acquired simultaneously, thus, questions arise regarding the correlation of the data for multiple locations that are acquired at different starting times. One method of correlating the data is to search for distinct structures or patterns in the data set that are repeated in time. For this technique to work, the data set must display self-correlating behavior. An experiment was performed in which the emission from the pool fire was acquired for a period of 15 minutes at a sampling rate of 100 Hz. Figure 3 displays the autocorrelation values for this experiment as a function of relative shift,  $N$ . It is evident that there is only high autocorrelation near  $N$  equal to zero. The low correlation values suggest that there is no dominant pattern that is repeated in time.

To determine the importance of correlation in calculating the heat flux, 19 non-simultaneous time series of temperature and soot volume fraction measurements for locations ranging from  $X/D$  (with  $R/D = 0.0$ ) from 0.2 to 2.0 in steps of 0.1 were analyzed using the following formula:

$$I_{\lambda} = I_{\lambda s}(1) \prod_{j=2}^N \tau_{\lambda s}(j) + \dots + I_{\lambda s}(M) \prod_{j=M+1}^N \tau_{\lambda s}(j) + \dots + I_{\lambda s}(N) \quad (1)$$

where:

$$I_{\lambda s}(M) = [1 - \tau_{\lambda s}(M)] I_{b\lambda}(M) \quad (2)$$

$$\tau_{\lambda s}(M) = \exp\left(-\frac{K_{\lambda} f_w \Delta S(M)}{\lambda}\right) \quad (3)$$

and  $I_{b\lambda}$  is Planck's function and  $I_{\lambda}(N)$  is the intensity reaching the fuel surface from the radiation from the  $N$  discrete locations. The integrated heat transfer to the surface was calculated using a) zero time shift, b) random time shift for every other data set and c) random time shift for all data sets. The calculations indicate that the heat transferred to the surface for all three cases were all within 1%. Further work is planned to develop methods of correlating data for different locations.

## MONTE-CARLO HEAT FLUX CALCULATIONS

For determining the total radiative flux to the fuel surface from the flame, the flux is computed as:

$$q_f = \int_0^{2\pi} \int_0^{\pi/2} \pi I_f(\theta_i, \phi_i) [2\cos\theta_i \sin\theta_i d\theta_i] [d\phi_i / (2\pi)] \quad (4)$$

where  $\phi$  is the azimuthal angle,  $\theta$  is the polar angle. That is, the flux is equal to  $\pi I_f(\theta, \phi)$  integrated over  $\theta_i$  and  $\phi_i$  with weighing functions of  $2\cos\theta_i \sin\theta_i$  and  $1/2\pi$  respectively. The flux can be estimated then by taking the average of many trial values of  $\pi I_f(\theta, \phi)$  evaluated at random values of  $\theta_i$  and  $\phi_i$  chosen using the weighting functions as probability density functions.

The evaluation of the flux requires the selection of a random direction ( $\theta_i, \phi_i$ ) and then the evaluation of the

incident intensity along that path. Using the appropriate pdf's, the random direction is chosen using:

$$\phi_i' = 2\pi R_\phi, \theta_i' = \arcsin(R_\theta) \quad (5)$$

where  $R_\phi$  and  $R_\theta$  are random numbers. After  $N$  trials using  $N$  directions the estimate  $q_i'$  is:

$$q_i' = \pi \sum_{j=1}^N \frac{I(\theta_j, \phi_j)}{N} \quad (6)$$

For each line integral, a ray is followed through a cylindrical geometry in which  $T$  and  $K$  (where  $K$  is the specific absorption coefficient) are known at a set of discrete values of  $R$  and  $X$ . The integration is performed by considering the cylindrical geometry as a stack of cylindrical rings. The values of  $T$  and  $K$  are known at the edges of the rings. The integral is estimated by combining the effects of each intersected ring.

For an isolated ring, the values of  $T$  and  $K$  can be linearly interpolated at the two points where a ray enters and leaves. Then the values of  $T$  and  $K$  are assumed to vary linearly between these two points in order to evaluate the intensity exiting the individual ring. The value of  $\tau$  is used to account for the absorption of radiation which simply passes through the ring when the effects of the individual rings are combined, and is given by:

$$\tau(s) = \exp\left(-\int_0^s K(s') ds'\right) \quad (7)$$

To form the entire line integral, the value of  $I_i$  is accumulated starting from the receiver at  $dA$ . Initially, the value of  $I_i$  for the path is set to zero, and  $\tau$  is set to 1. As each ring is encountered, the intensity is incremented by the intensity exiting from that ring in isolation, attenuated by the value of  $\tau$  for the rings between the current ring and  $dA$ . The value of  $\tau$  then is reduced by multiplying by the value of  $\tau$  for the isolated ring to appropriately attenuate radiation from rings intersected further away from  $dA$ .

## DISCUSSIONS

Optical measurements of the temperature and soot volume fraction of a pool fire burning heptane have been performed. The average soot volume fractions were approximately an order magnitude smaller in the heptane fire as compared to the toluene fires [3]. The average temperatures were several degrees higher than in toluene fires.

The ionization gauge was used to distinguish between conditions of low-temperature within the reaction zone and conditions in which the flame is not residing within the probe volume. This information is necessary for determining the method of treatment for low emission data.

A reverse Monte Carlo radiative heat transfer model has been formulated to calculate the burning rate of the pool fire. The spatial and temporal measurements of the temperature and  $f_v$  will be used to calculate the radiative feedback to the surface and the burning rate for comparisons with the experimental measurements.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the helpful discussion and advice provided by Dr.W.L. Grosshandler of NIST and Professor J.P. Gore of Purdue University.

## REFERENCES

1. Markstein, G.H., Eighteenth Symposium (Int'l) On Combustion, The Combustion Institute, Pittsburgh, p. 1055, (1981).
2. Choi, M.Y., Hamins, A., Mulholland, G.W. and Kashiwagi, T., "Simultaneous Optical Measurement of Soot Volume Fraction and Temperature", Comb. Flame, Submitted, 1993.
3. Klassen, M., Sivathanu, Y.R. and Gore, J.P., Comb. Flame, 90, p.34, (1992).

Fig. 1:  $T$ ,  $f_{ve}$  and  $f_{va}$  as a function of radial position

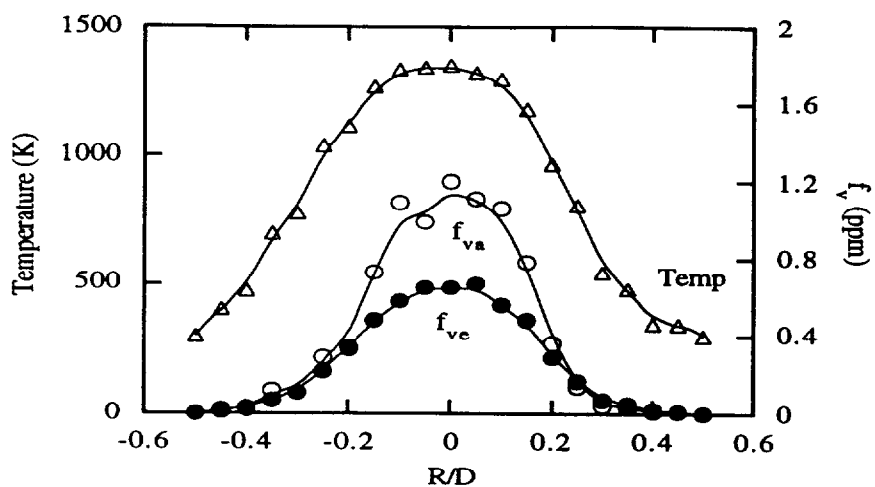


Fig. 2: Cross-correlation of dual ionization voltages as a function of distance

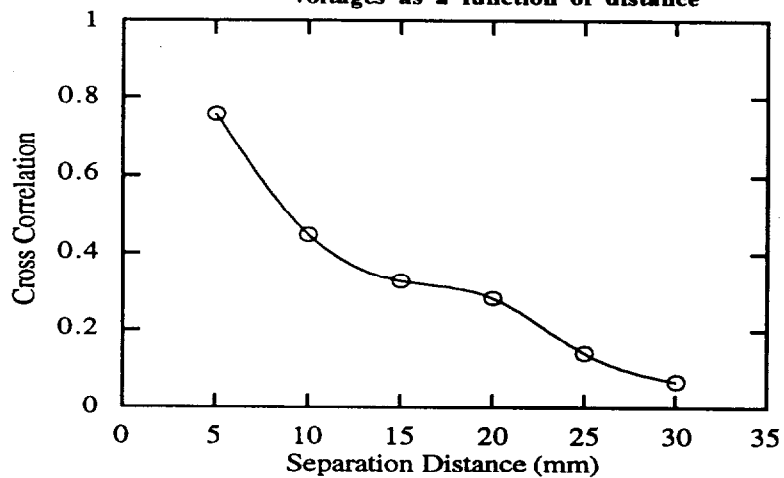


Fig. 3: Auto-correlation of emission data

