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Laser-diagnostic mapping of temperature and soot statistics in a 2-m diameter turbulent pool fire

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ABSTRACT

We present spatial profiles of temperature and soot-volume-fraction statistics from a sooting, 2-m base diameter turbulent pool fire, burning a 10%-toluene/90%-methanol fuel mixture. Dual-pump coherent anti-Stokes Raman scattering and laser-induced incandescence are utilized for simultaneous point measurements of temperature and soot. The research fuel-blend used here results in a lower soot loading than real transportation fuels, but allows us to apply high-fidelity laser diagnostics for spatially resolved measurements in a fully turbulent, buoyant fire of meter-scale base size. Profiles of mean and rms fluctuations are radially resolved across the fire plume, both within the hydrocarbon-rich vapor-dome region near fuel pool, and higher within the actively burning region of the fire. The spatial evolution of the soot and temperature probability density functions is discussed. Soot fluctuations display significant intermittency across the full extent of the fire plume for the research fuel blend used. Simultaneous, spatially overlapped temperature/soot measurements permit us to obtain estimates of joint statistics that are presented as spatially resolved conditional averages across the fire plume, and in terms of a joint pdf obtained by including measurements from multiple spatial locations. Within the actively burning region of the fire, soot is observed to occupy a limited temperature range between ~1000 and 2000 K, with peak soot concentration occurring at 1600–1700 K across the full radial extent of the fire plume, despite marked changes in the local temperature pdf across the same spatial extent. A wider range of soot temperatures is observed in the fuel vapor-dome region low in the pool fire, with detectable cold soot persisting into conditionally averaged statistics. The results yield insight into soot temperature across a wide spatial extent of a fully turbulent pool fire of meaningful size, which are valuable for development of soot radiative-emission models and for validation of fire fluid-dynamics codes.

1. Introduction

Fire is a leading threat to the security of transportation systems and critical infrastructure, and is a critical factor in life-safety considerations. Improved computational tools for risk assessment increasingly rely upon solid physical underpinnings for predictive simulation of fire phenomena. Fire fluid-dynamics codes must capture complex, multi-physics effects, encompassing turbulent mixing, chemical reaction, and the thermal radiative transport that is a product of the reacting flow—all in a three-dimensional system that is several meters or more in size. To achieve realistic, fully turbulent conditions, buoyancy-dominated fire plumes must be at least 1 m in base size [1,2]. At this length scale, simulations are costly, so that detailed experiments are extraordinarily valuable for development of subgrid and engineering models that make calculations more tractable, and for validation of fire simulations.

Radiative heat transfer from hot soot is the primary threat from a fire-accident scenario. In the absence of scattering, the radiative transfer equation along a linear path, s, through the fire plume is given by

$$\overline{\frac{dI_\lambda(s)}{ds}} = \overline{\mu_\lambda(s) I_{\lambda,b}(s;T)} - \overline{\mu_\lambda(s)}\;\overline{I_\lambda(s)}, \tag{1}$$

where the overbars represent time averaging. I_λ is the spectral radiative intensity along s; $I_{\lambda,b}$ is the blackbody spectral intensity at the local temperature, T; and μ_λ is the soot absorption coefficient. The soot-volume-fraction, f_v, dependence of μ_λ is $\mu_\lambda = g(n) f_v/\lambda$, where g is a function of the soot refractive index, n, and λ is the wavelength [3]. Experimental validation of Eq. (1) then requires measurement of the local temperature and soot volume fraction along a path through the fire plume, and this expression simply states that the change in radiation intensity along s is emission minus absorption. In the absorption term, μ_λ and I_λ may be treated with independent time-averaging operations because correlation is weak between the radiative intensity, which is influenced by

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long-range contributions, and μ_λ, which is entirely determined by the structure of the local soot field. Soot radiative emission, represented by the first term on the right-hand side of Eq. (1), originates from thin soot layers [4–8], where high gradients in both temperature, and soot concentration may exist. Correlation between these two locally determined quantities can be quite significant, and the $\mu_\lambda I_{\lambda,b}$ product must be averaged as a single quantity, necessitating simultaneous space- and time-coincident temperature/soot measurements. Ideally, sufficient sampling should be acquired to obtain estimates of the joint pdf of the temperature and soot fluctuations, which can then be utilized to develop emission source terms for fire heat-flux calculations in turbulent flames and fire plumes.

Simultaneous space- and time-resolved measurement of temperature and soot in a turbulent combustion environment represents a significant measurement challenge, but some examples can be found in the literature. Emission probes provide a direct measurement of soot temperature integrated over a volume, and can be coupled with laser light extinction to yield soot f_v. Sivathanu and Faeth [9] report simultaneous T/f_v data from laboratory-scale, buoyant, turbulent diffusion flames using two-color pyrometry and laser light extinction. The measurements were path integrated over a 1- to 2-cm extent, with a corresponding volumetric spatial resolution of 0.067–0.135 cm^3. They presented temperature probability densities (pdf) conditioned on soot f_v, which revealed that soot exists in a relatively narrow range of temperatures within the underfire (fuel-rich) region, and additionally analyzed scalar state-relationship data from earlier work [10,11] in the overfire (fuel-lean) region to infer a much wider range of soot temperatures there. More recently, Mahmoud and co-workers [6] performed highly spatially resolved, two-dimensional T/f_v imaging in a sooting turbulent jet flame, using laser-induced fluorescence of indium and soot laser-induced incandescence (LII). These data were used to estimate soot pdfs conditioned on temperature. Their conclusions regarding soot temperature history were consistent with Sivathanu and Faeth's [9]; soot experiences a narrow range of temperatures low in the flame and early in its history, and then proceeds to occupy a larger range of temperatures with increasing residence time, as it is transported upward and experiences a variety of conditions relative to the reaction zone. Mahmoud et al. [6] examined their joint T/f_v pdf data to conclude that soot temperature displayed little radial dependence, and that the horizontal structure of the mean soot profile was due solely to the increase in intermittency of soot fluctuations with radial distance. Mahmoud *et al.* observed log-normal conditional soot pdfs across the full range of temperatures, which is associated with a high degree of intermittency in soot turbulent fluctuations. Soot intermittency is a well-known phenomenon, and has been observed in LII measurements in jet flames [5,12,13], buoyancy dominated flames at lab scale [4,7], and meter-scale pool fires of moderate sooting propensity fuels [8].

We located two studies devoted to simultaneous T/f_v measurements in fully turbulent, meter-scale pool fires. Gritzo et al. [14] deployed a water-cooled optical probe in a 6-m JP-8 pool fire and report pyrometer temperatures and emission/absorption soot volume fractions within a 2-cm-long × 1-cm-diameter sampling volume. Their results revealed a conditionally averaged soot temperature that was essentially invariant to soot concentration at a single location near the center of the fire plume. Murphy and Shaddix [15] used a similar fiber-optically coupled diode-laser probe to Gritzo et al. for extinction/absorption measurements of soot volume fraction, along with two-color pyrometry, in a 1-m-diameter, turbulent JP-8 pool fire. The measurement path length was 3.6 cm and the collection aperture was 5.5 mm. Soot pdf data conditioned on emission temperature displayed a departure from the log-normal form observed by others in turbulent jet flames [5,7] and pool fires of more lightly sooting liquid fuel blends [8], representing significant reduction in the intermittency of soot fluctuations within the interior of these heavily sooting fire plumes.

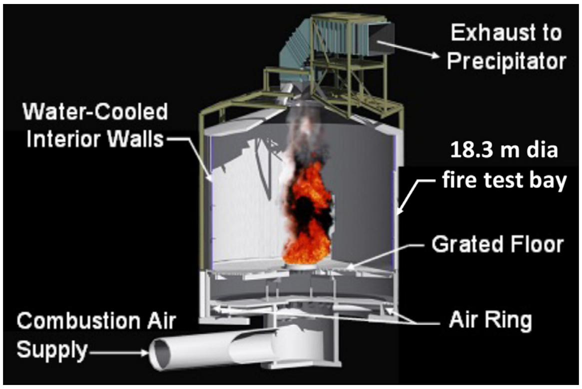

Fig. 1. Essential elements of the FLAME test bay. The main fire test bay is 18.3 m in diameter and 12.2 m in height when measured from the grated-floor ground plane.

These earlier pool-fire measurements, while revealing, were still limited in their volumetric spatial resolution (0.8–1.5 cm^3), and subject to the usual assumptions associated with two-color pyrometry. We have more recently described laser-diagnostic instrumentation for temperature and soot measurements in meter-scale fire plumes at volumetric spatial resolutions as fine as $10^{-4}\,\text{cm}^3$ for temperature and $10^{-5}\,\text{cm}^3$ for soot by utilizing dual-pump coherent anti-Stokes Raman scattering (CARS) thermometry [16,17] and soot LII [8]. This work was facilitated by Sandia's Fire Laboratory for Accreditation of Models and Experiments (FLAME) facility [18], which allows for controlled meter-scale burns with integrated laser diagnostics. Our earlier work demonstrated capability, but provided limited data at only a single measurement location, and for a restricted number of laser shots and fire realizations that was too small for meaningful statistics to be generated. In this article, we will present the application of these laser-diagnostic tools in a more significant data campaign, where temperature/soot statistics were mapped across the radial extent of a 2-m base diameter fire plume at three vertical heights above the fuel surface. Large ensembles consisting of tens of thousands of single-laser-shot measurements at each spatial location, obtained over multiple fire experiments, are used to gather more meaningful statistical results. We present the data here in terms of radial profiles of temperature and soot statistical quantities and provide joint statistical estimates in the form of both mean soot and soot pdf, both conditioned on CARS temperature data.

2. FLAME facility and pool fire structure

The design and construction of FLAME (Fire Laboratory for Accreditation of Models and Experiments) is shown in Fig. 1, and is described in significant detail by Blanchat et al. [18], and by Kearney et al. [16]. Briefly, a 2-m fuel pan is located at the center of an 18.3-m diameter × 12.2-m high main test bay level, whose water-cooled walls provide a well-controlled ambient temperature far-field condition. Combustion air is provided at flow rate of 33,000 SLPM through a well-balanced air ring at the periphery of the FLAME basement and entrained through steel-grated flooring at the perimeter of the main test-bay level. The resulting co-flow bulk velocity was 0.24 m/s. A smooth ground plane is provided by a 12-m outer-diameter steel skirt that surrounds the fuel pan. Constant liquid fuel level is maintained within ±1 mm of the desired height, just below the pan tip, by supplying fuel at a rate determined by real-time monitoring of the surface liquid level via hydrostatic pressure in the fuel pool. A research fuel blend of 10% toluene by volume in a balance of methanol is used in our