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Spectral radiation intensities of a turbulent buoyant ethylene flame: CFD-aided tomographic inversion

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ABSTRACT

Radiation heat transfer has been found to dominate fire spread in large-scale fires. The radiation heat loss of buoyant turbulent fires is coupled with fluid mechanics, combustion processes, and soot/gas concentrations. Deconvolution of these combined phenomena can facilitate the development of combustion and radiation models for use in predictive fire modeling. Therefore, in this work, line-of-sight spectral radiation intensities have been measured from a buoyant turbulent pool-fire-like ethylene diffusion flame. In an attempt to be representative of practical turbulent fires, a burner of 15.2 cm in diameter was used. Temporal measurements of radiation intensity were obtained with a fast (400 Hz) mid-infrared spectrometer at a horizontal plane located at half a burner diameter above the burner. Measurement statistics, including mean, root mean square (RMS), probability density function (PDF) of line of sight intensity, and intermittency are reported herein for wavelengths dominated by soot and CO_2 radiation. The data show that radiation is affected by large-scale vortical motions, resulting in varying flame intermittency in the radial direction. Radial distributions of local scalar properties (temperature and soot volume fraction) were calculated through tomographic inversion, using measured data at multiple soot radiation wavelengths. The inversion technique was coupled with the results of a computational fluid dynamics (CFD) fire simulation code. CFD results were used to construct PDFs and spatial correlations for the scalars of interest. The estimated scalars are shown to be consistent with values from the literature, and mean and RMS radiation intensities computed from these scalars are in good agreement with measurements.

1. Introduction

Radiation heat transfer has been found to dominate fire spread in large-scale fires. Buoyancy-driven pool fires have received considerable attention (e.g. [1–9]) as a canonical problem to study flame dynamics and thermal radiation. In these flames, periodic large-scale oscillatory motions (or puffing) occur with a frequency inversely proportional to the square root of the pool diameter [10]. Air is entrained into the fire by large vortex structures that originate near the fire base [11] by Rayleigh-Taylor (RT) instabilities. These vortices go through a turbulent cascade and transfer energy to smaller scale fluctuations. Turbulence generation also takes place at small scales due to RT instabilities [12]. The radiation of turbulent buoyant fires is greatly influenced by fluctuations/pulsations in the scalar fields introduced by the aforementioned processes. Deconvolution of these combined phenomena can facilitate the development of radiation models for use in predictive fire simulations.

Measurements of radiation and scalar properties of buoyancy-driven pool fires have been conducted on flames of different sizes. Sivathanu and Faeth [1] and Klassen et al. [2,3] measured temperature and soot volume fraction statistics of buoyant turbulent pool fires (established in 5 cm and 7.1 cm diameter burners, respectively). Xin and Gore [4] measured spatially resolved soot distributions for methane and ethylene buoyant turbulent flames, in a 7.1 cm diameter burner. Gritzo et al. conducted in-situ measurements of soot properties in a large (6×6 m^2) JP-8 pool fire using a multi-wavelength absorption/emission probe [6]. Murphy and Shaddix further applied this diagnostic to obtain this measurement at multiple locations in a 2 m diameter JP-8 pool fire [7]. Kearney et al. used dual-pump coherent anti-Stokes Raman scattering to measure temperature of turbulent fires of meter-scale [8]. Rankin et al. [9] applied an LES model-based flame imaging approach for a weakly radiating jet flame and demonstrated that this technique offers a complementary approach for analyzing the scalar flow-field. Recently, several studies conducted line-of-sight measurements of spectral radiation intensities (I_λ) for buoyant [5] and momentum-dominated [13–15] flames using a fast

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Nomenclature

a	random shock
cv	coefficient of variation
d	pathlength
f_v	soot volume fraction (ppm)
I	radiation intensity (kW/m^2-sr)
m	complex index of refraction of soot
R	Burner radius (m)
r	radius (m)
T	temperature (K)
t	time (s)
x	distance from diametric line (m)

Greek

θ	normalized temperature
κ	absorption coefficient
λ	wavelength
ρ_{12}	cross-correlation coefficient
σ	standard deviation
τ	transmissivity

Subscripts

c	soot temperature critical value
bλ	blackbody
i	segment index
j	segment index
s	CFD simulation
λ	wavelength

infrared array spectrometer (FIAS) [16], or using both a FIAS and a mid-infrared camera [9]. Such measurements do not require introducing an object into the flame, however, they provide convoluted information of the related scalar properties and their correlations. Stochastic time and space series (TASS) analyses have been applied to simulate scalar fluctuations of momentum-dominated turbulent flames [13,15,17,18]. The mean and RMS values of scalars were inversely calculated based on measured radiation intensities from different line-of-sight paths. Biswas et al. [5] extended such a tomographic inversion method to buoyancy-driven pool fires (7.1 cm diameter burner). The temperature and soot volume fractions were modeled using a two-variable clipped joint PDF. However, the PDFs of these scalars may vary significantly within the fire due to the effect of vortical motions, which makes it difficult to apply a universal PDF function to all locations in the fire. In addition, the multi-location spatial correlations of the scalars along the line-of-sight are important for calculating mean absorption as well as RMS values of radiation intensity. It is very challenging, if not impossible, to use statistical methods to enforce the physical spatial correlations while maintaining the desired PDF for each location.

On the basis of the above discussion, the present study seeks to achieve the following:

1. Measure temporal spectral radiation intensities of steady pool-fire-like flames and obtain statistical quantities from the measurements, such as mean, RMS, PDF, and intermittency.
2. Given that computational fluid dynamics (CFD) fire simulation tools have evolved to have a good degree of fidelity and predictiveness in regards to fire plumes [19], model the flame structure of the studied fire to obtain PDFs and spatial/temporal correlation coefficients for the scalars of interest.
3. Combine the results from CFD simulations with tomographic inversion and optimization to calculate radial distributions of mean and RMS temperatures and soot volume fractions. The measured radiation intensity data at multiple wavelengths are used as the optimization target. The inversed soot temperature and volume fraction information can be applied to facilitate the development and validation of the soot/radiation modeling in CFD models.

2. Experimental approach

2.1. Apparatus and instrumentation

The apparatus consisted of a steel round burner with diameter of 15.2 cm and height of 12.7 cm. A steady-state buoyant turbulent ethylene (chemically pure grade, 99.5%) diffusion flame was established on the burner with a heat release rate of 14 kW (mass flow rate of 0.292 g/s and Froude number of 0.08 [20]). The fuel flow rate was maintained constant by a mass flow controller (Sierra C100M-DD-3-OV1-SV1-PV2-S0) and fed through a port located at the bottom of the burner. Uniform exit velocities over the burner surface were ensured by using two layers of coarse and fine sand (25.4 and 50.8 mm thickness, respectively). At the exit plane, the sand was flush with the burner lip. The burner was surrounded by an air co-flow (0.3 m diameter, 0.14 m/s velocity normal to burner surface) to reduce the effects of ambient drafts. The burner surface temperature was measured using type-K thermocouples, and the mean temperature value was used as the fuel inlet temperature condition in the CFD simulation.

Line-of-sight (LOS) spectral intensity measurements were conducted with an FIAS for the diametric and 12 parallel chord-like paths at half a diameter height (7.6 cm) above the burner, see Fig. 1. The approximate height of measurement is also shown with a flame image. The FIAS's sampling rate was 400 Hz; its spectral range was 1–5 µm (20 nm resolution), approximately, covering the near-infrared soot

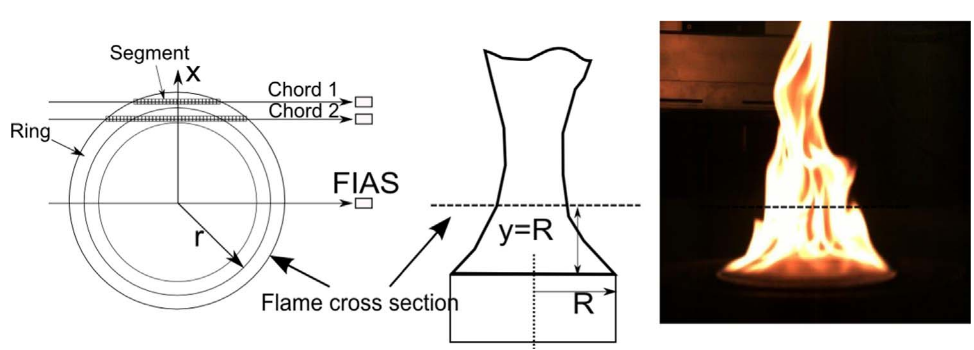

Fig. 1. Geometry for spectral radiation intensity measurement and calculation.