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Quantitative imaging of radiation from soot and carbon dioxide in a turbulent ethylene jet diffusion flame

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ABSTRACT

Quantitative imaging of mid-infrared radiation provides a unique capability to investigate temporally and spatially resolved radiation from gas species and particulates in turbulent flames. The current study reports and analyzes quantitative images of radiation intensity from a turbulent ethylene jet diffusion flame that matches the Reynolds number (15,200) of a non-sooting flame (DLR-A) from the International Workshop on Measurement and Computation of Turbulent Non-premixed Flames. A calibrated high-speed mid-infrared camera with two band-pass filters was used to acquire images of radiation intensity in wavelengths corresponding to soot and carbon dioxide. The measurements, in the wavelength band corresponding to radiation emissions from soot, show thin radiating structures corresponding to soot layers. The normalized probability density functions (PDFs) of soot radiation are skewed by intermittent high intensities while the PDFs of carbon dioxide radiation are more symmetric about the mean. The temporal and spatial integral scales of radiation from soot are up to 30% shorter than the corresponding scales of radiation from carbon dioxide for image centerline locations downstream of initial soot radiation detection. The images and analyses in this work will be compared with results of large eddy simulations rendered in the form of quantitative images of the mid-infrared radiation intensity. Such comparisons support the evaluation of models used in turbulent combustion and radiation simulations.

1. Introduction

Turbulent sooting flames are important to many combustion applications such as industrial furnaces, gas turbine engines, and fire safety. Radiation heat transfer can affect soot formation, oxidation, and emission. The incorporation of radiation effects into computational models of sooting flames is important to estimate flame temperature, which in turn controls soot formation and oxidation rates [1]. It is also necessary to consider the coupling of radiation with turbulence and chemistry to model soot formation [2–4].

Medwell et al. [5] demonstrated that concentrated irradiation on an ethylene flame increases soot volume fractions through molecular excitation and heating of soot particles. Gore and Faeth [6] investigated the spectral radiation characteristics of turbulent ethylene/air diffusion flames. The work concluded that the effects of turbulence/radiation interactions were more significant for continuum radiation from soot than for 4.3 μm gas band radiation from carbon dioxide. Zheng and Gore [7] measured spectral radiation intensities utilizing a fast infrared array spectrometer (FIAS) and applied emission tomography and inverse radiation techniques to estimate radial profiles of temperature and soot volume fractions. The work emphasized the need for acquiring benchmark experimental data of luminous flames similar to the International Workshop on Measurement and Computation of Turbulent Non-premixed Flames (TNF Workshop) [8]. Imaging techniques such as Laser Induced Incandescence (LII), Planar Laser Induced Fluorescence (PLIF), and Particle Image Velocimetry (PIV) have contributed significantly to the understanding of turbulent sooting flames [9–14]. Representative sooting flames with well-defined operating conditions have emerged from the International Sooting Flame (ISF) Workshop [15]. Data are needed for guiding advanced computational models of resolved scale and subgrid scale soot processes.

Incorporating radiation into models of sooting flames has been shown to be important in several studies. The radiation model can affect both qualitative and quantitative agreement between measurements and computations [16,17]. Snegirev [18] used a gray continuous radiation model to include the effects of soot radiation on the properties of buoyant turbulent diffusion flames. Modest and colleagues [19–22] applied gas-phase chemistry and soot models validated for laminar flames to turbulent flames and found good agreement with measured temperatures, soot volume fractions, and radiation heat fluxes. Zimberg [23] and Desjardin [24] applied a range

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of soot radiation models to large eddy simulations (LES) resulting in reasonable estimates of temperatures. Wang et al. [1] concluded that radiation intensity measurements were important for validation of large eddy simulations and subgrid scale models of soot formation and oxidation processes.

Quantitative imaging of mid-infrared radiation intensity provides new insights and data for comparison with computational results [25,26]. The quantitative mid-infrared imaging method has been demonstrated as a useful technique for evaluating flame instability magnitudes and frequencies, observing flame stabilization regions, and calculating turbulent radiation statistics in the plume region [27,28]. Schefer et al. [29] utilized infrared imaging of a large-scale hydrogen flame to quantify flame lengths and radiation statistics. Rankin et al. [25] quantitatively rendered images of radiation intensity of nonluminous flames by utilizing LES scalar values combined with a narrowband radiation model (RADCAL) [30]. Computational images of the radiation intensity were displayed in a format that allowed direct comparison with experimental observations. The quantitative comparison of measured and computed images demonstrated that including radiation heat loss effects is important even for weakly radiating flames with low radiant heat loss fractions (e.g. less than 10%) particularly in the region downstream of the stoichiometric flame length.

The work reported in this paper extends the quantitative mid-infrared imaging measurements to soot containing luminous flames. The specific objectives are as follows:

1. Measure time-dependent and time-averaged quantitative images of radiation intensity from soot and carbon dioxide for a well documented standard turbulent ethylene jet diffusion flame;
2. Examine the radiation statistics including mean, root mean square (RMS), probability density functions, skewness, kurtosis, temporal correlations, and spatial correlations; and
3. Compare and contrast the temporal and spatial radiation statistics of soot and carbon dioxide radiation.

2. Experimental methods

2.1. Flame and coordinate system

The nonpremixed turbulent ethylene flame was established on a 480 mm long tube tapered to a thin edge with a nominal inner diameter (D) of 8 mm. The selection of a turbulent ethylene diffusion flame established on a burner with well-defined boundary conditions is ideal for comparing measurements and computations of turbulent sooting flames [12,25,26]. An ethylene flow rate of 993 mg/s was selected to match the Reynolds number (15,200) of a representative nonluminous turbulent flame (DLR-A) from the TNF Workshop [8] and is consistent with a past study of turbulence-radiation interactions [7]. The Reynolds number was calculated based on cold gas properties, the exit velocity, and exit diameter. The mass flow rate was calibrated using a dry test turbine meter and controlled by setting the pressure upstream of a choked orifice plate.

Figure 1 illustrates the experimental arrangement for the flame and radiation intensity measurements. The flame coordinate system (x, r, θ) was defined with an origin located at the center of the burner exit. The camera coordinate system (X, R, Y) was defined with an origin located at $(x, r, \theta) = (0, d, 0)$ where d is the distance between the camera lens and the flame axis. The burner was mounted on a traverse mechanism allowing multiple flame heights to be observed.

2.2. Radiation intensity measurements

Time-dependent images of the radiation intensity emitted from the turbulent ethylene flame were measured using a calibrated high speed mid-infrared camera with an indium antimonide (InSb) focal plane array (320 × 256 pixels). The camera was positioned 50 cm from the flame centerline. The spatial resolution was approximately 0.61 mm for each pixel of the focal plane array. Two band-pass filters were used to measure radiation from only soot (S) (3.71 ± 0.07 μm) and from both carbon dioxide and soot (CO_2+S) (4.34 ± 0.10 μm). A neutral density filter with a transmittance of approximately 32% (i.e. optical density of 0.5) was utilized in conjunction with the 4.34 μm filter to prevent saturation of the camera detector. The camera measured spectrally integrated radiation intensity along approximate lines of sight through the flame as shown in Fig. 1 and described by the solution to the radiative transfer equation for absorbing-emitting media without incident radiation [25],

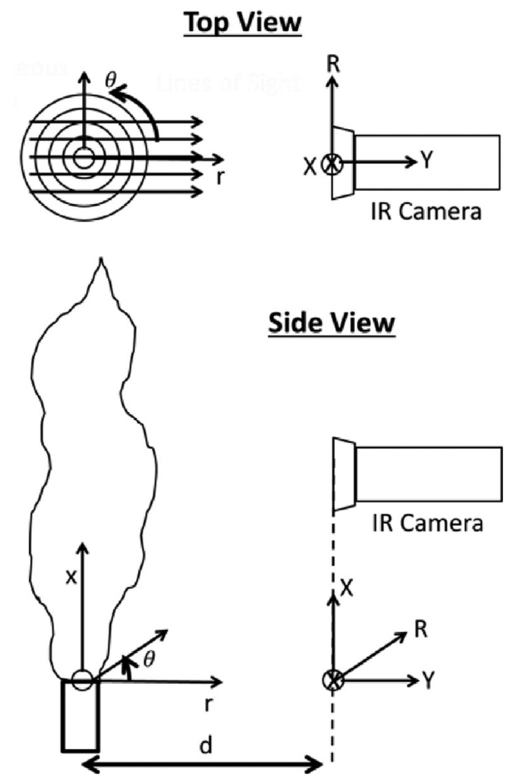

Fig. 1. Experimental arrangement for acquiring quantitative images of the radiation intensity from the turbulent sooting flame.

$$I = \int_{\lambda_1}^{\lambda_2} \tau_{\lambda,filters} \int_0^{\tau_\lambda} I_{b\lambda}\left(\tau_\lambda^*\right) e^{-\left(\tau_\lambda - \tau_\lambda^*\right)} d\tau_\lambda^* d\lambda. \quad (1)$$

$I_{b\lambda}$ is the blackbody spectral intensity and λ_1 and λ_2 are the spectral limits of the band-pass filter. $\tau_{\lambda,filters}$ accounts for transmission losses through the filter and lens and the spectral response of the camera focal plane array as demonstrated by Rankin et al. [25,26]. The optical thickness (τ_λ) is defined as [25],

$$\tau_\lambda = \int_0^s \kappa_\lambda ds, \quad (2)$$

where κ_λ is the spectral absorption coefficient and s is the path length. The chord-like paths through the flame are parallel to within less than 9° based on the camera optics (25 mm, f/2.3 lens) and distance from the camera lens to the flame axis. The optical arrangement results in a solid angle of 0.4 milli-steradians associated with each pixel. The depth-of-field is estimated to be +/- 5 cm based on the thin-lens approximation.

The camera was calibrated using a high temperature cavity blackbody radiation source positioned at the same distance from the camera as the flame centerline to account for the effect of atmospheric absorption. Radiation absorption from water vapor in the surroundings is negligible at the wavelengths used in this work. Transmission