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Quantitative model-based imaging of mid-infrared radiation from a turbulent nonpremixed jet flame and plume

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ABSTRACT

Current understanding of turbulent reacting flows can be improved by novel quantitative comparisons using highly scalable visualization methods based on volume rendering of time-dependent mid-infrared intensities in the form of images with multiple view angles. In this work, the effects of radiation and buoyancy in a turbulent nonpremixed flame and plume are studied by quantitatively comparing measured and computed images of the mid-infrared radiation intensity. To this end, a turbulent nonpremixed jet flame (Reynolds number 15,200 and $CH_4/H_2/N_2$ fuel composition) is considered, representing a benchmark flame configuration of the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames (TNF Workshop). Quantitative images of the radiation intensity from the flame are acquired using a calibrated high-speed mid-infrared camera and band-pass filters. The camera and filters enable time-dependent measurements of radiation from water vapor and carbon dioxide over the entire flame length and beyond. Results of the solution to the radiative transfer equation are rendered in the form of images using scalar values from large eddy simulations (LES) and a narrowband radiation model. Planar images obtained from experiments and simulations for the radiation intensity display qualitatively comparable features, including localized regions of high and low intensity that are characteristic of turbulent flames. The quantitative comparison of the measured and computed temperature profiles and radiation intensities, particularly in the plume region downstream of the stoichiometric flame length, indicate that including radiation heat loss is important even for weakly radiating flames. The results demonstrate that quantitative experimental and model-based imaging of mid-infrared radiation intensity is useful for assessing the results of narrowband radiation and combustion models.
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1. Introduction

Significant progress has been made toward quantifying the importance of radiation transfer in turbulent flames over the past fifteen years. Experimental and computational studies of radiation transfer in non-luminous turbulent nonpremixed and partially premixed jet flames have utilized an extensive range of techniques such as radiation heat flux measurements [1], spectral radiation intensity measurements [2,3], stochastic time and space series analyses [2,3], conditional moment closure calculations [4], composition probability density function calculations [5,6], Monte Carlo simulations [7], and most recently large eddy simulations (LES) [8–10]. Progress on radiation transfer computations for turbulent reacting flows and combustion systems have been the focus of several review articles [11–16].

Significant opportunities exist for improving radiation and combustion models for turbulent nonpremixed and partially premixed flames, building on the progress discussed in the cited Refs. [1–16]. The opportunities are supported partially by emerging imaging technologies (e.g. calibrated high-speed imaging of mid-infrared radiation [17–20]) and advanced simulation capabilities (e.g. LES and direct numerical simulations). Relatively recent advancements in high speed, high resolution planar sensors with sensitivity in relevant mid-infrared spectral wavelengths make it feasible to acquire quantitative images of mid-infrared radiation measurements from carbon dioxide (CO_2), water vapor (H_2O), carbon monoxide (CO), and methane (CH_4). This capability is utilized in this work to contribute time-dependent imaging measurements of the radiation intensity from a representative turbulent nonpremixed flame with operating conditions defined by the TNF Workshop [21].

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Nomenclature

Symbols

a_p	Planck mean absorption coefficient
C	reaction progress variable
C_p	specific heat capacity at constant pressure
c_0	speed of light in a vacuum
C_1	first radiation constant ($2\pi hc_0^2$)
C_2	second radiation constant (hc_0/k)
d	distance between flame axis and camera
D	nominal inner diameter of burner
D_t	substantial derivative ($\partial_t + u \cdot \nabla$)
Fr	Froude number ($U_j/\sqrt{gD}$)
g	acceleration due to gravity
h	Planck's constant
H	enthalpy (Eq. (5))
I	radiation intensity
$I_{b\lambda}$	blackbody spectral radiation intensity $[C_1/(\lambda^5(e^{C_2/\lambda T}-1))]$
k	Boltzmann's constant
p	partial pressure
$\dot{q}_r$	radiation heat loss (Eq. (6))
r	flame (observed) radial coordinate
R	camera (observer) transverse coordinate
Re	Reynolds Number ($\rho U_j D/\mu$)
s	path length
T	temperature
u	velocity vector
U_j	mean bulk jet exit velocity
x	flame (observed) axial coordinate
X	camera (observer) axial coordinate
Y	mass fraction
Z	mixture fraction
α	molecular diffusivity
α_λ	spectral optics coefficient
ΔH_f^0	heat of formation
θ	flame (observed) azimuthal coordinate
κ_λ	spectral absorption coefficient
λ_1, λ_2	filter bandwidth wavelength limits
μ	dynamic viscosity
ρ	density
σ	Stefan–Boltzmann constant
τ^{res}	subgrid turbulent fluxes
τ_λ	spectral optical thickness (Eq. (8))
χ	scalar dissipation rate
$\dot{\omega}$	chemical reaction rate

Subscripts

i	species i
∞	surrounding environment
λ	wavelength

The advancements in mid-infrared imaging technologies can be complemented by the development of corresponding quantitative visualization and volume rendering methods for displaying three-dimensional time-dependent simulation results in the form of images with consideration of time and length scale that vary over orders of magnitude. Computational flow imaging allows results from theoretical calculations to be displayed in a format that mimics experimental observations [22]. Volume rendering is one technique for creating two-dimensional images from three-dimensional discretely sampled computations or measurements [23–26].

The capability to visualize three-dimensional time-dependent results of fire simulations has been advanced by the development of the Fire Dynamics Simulator and Smokeview programs [27]. Smokeview has made the results from fire simulations more accessible by displaying two and three-dimensional temperature and gas species concentration distributions, velocity fields, and particle paths in an effective manner that allows further insights [27]. The rotation of two-dimensional scalar profiles about the flame axis coupled with false coloring techniques has been used to compute qualitative visible images of soot containing laminar diffusion flames [28,29]. These studies demonstrated that the qualitative comparison of measured and computed planar results is a useful tool for assessing soot formation models in luminous regions of laminar flames. The quantitative comparison of measured and computed images of the radiation intensity from bluff-body stabilized laminar diffusion flames revealed good agreement in the size and shape of the flames and important differences in the flame stabilization region, suggesting improvements in the modeling of soot formation and heat losses [17].

The effects of scalar fluctuations on radiation transfer in turbulent flames have been quantified in several computational studies. For example, composition probability density function calculations of partially premixed jet flames demonstrated that including radiation decreased the peak temperature by 60–330 K with the larger temperature decrease corresponding to flames with larger optical thicknesses [5]. Including turbulence radiation interactions (TRI) further decreased the peak temperature by 20–120 K [5]. Therefore, TRI accounts for approximately one-third of the temperature decrease caused by radiation.

The effects of TRI in LES and the relative importance of subgrid-scale (SGS) and resolved-scale fluctuations have been receiving increased attention over the last few years [9,10,30–32]. Some studies have suggested that the SGS radiation emission should be considered, and the SGS radiation absorption can be neglected for homogeneous isotropic turbulence [30,31]. Evidently, the largest contribution to the filtered radiation emission and absorption terms could be accounted for using resolved scale scalars. LES of nonluminous and luminous turbulent nonpremixed flames have been investigated using filtered density function, photon Monte Carlo, and line-by-line models [10]. The SGS fluctuations contributed more to emission TRI than the resolved scale fluctuations for LES in which approximately 84% of the turbulence kinetic energy is resolved [10]. Therefore, including a SGS model in LES computations is important for flames in which emission TRI is significant. The contribution of SGS fluctuations to absorption TRI is negligible in comparison to the contribution of the resolved scale fluctuations. Quantitative evaluation of the importance of including a SGS model for emission TRI in laboratory-scale flames and practical combustion systems is an active and important research direction. This work is focused on developing a novel method for quantitatively comparing measurements and simulations of mid-infrared radiation intensities. The lessons learned from the comparisons are expected to support improvement and development of SGS closure models for the description of turbulence radiation interactions.

Turbulent flame experiments that consider several operating conditions and utilize a range of radiation intensity measurements with adequate spatial and temporal resolution are needed to assist the computational studies previously described. The development of corresponding novel quantitative image rendering approaches is needed for comparing measurements and computations with consideration of resolved and unresolved time and length scales. Motivated by these considerations, the primary objectives of this work

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