Model-Based Imaging of Infrared Radiation Intensity from a Turbulent Non-Premixed Jet Flame and Plume

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Radiation transfer within and from turbulent reacting flows is important in many applications related to combustion, energy, propulsion, and fire safety. Advanced measurements and computations of radiation transfer are essential for improving efficiencies, managing emissions to the environment, predicting combustor durability, and controlling unwanted fires. Emerging large scale computations can benefit from the development of highly scalable quantitative visualization methods for volume rendering and displaying three-dimensional time-dependent results in the form of planar images with consideration of time and length scales that vary over orders of magnitude. In this work, experimental and computational methods for quantitatively comparing measured and modeled images of the infrared radiation intensity from a representative turbulent non-premixed jet flame and plume are developed. Quantitative images of the radiation intensity from the flame are acquired using a high speed infrared camera. Results of the solution to the radiative transfer equation are rendered in the form of planar images using a narrowband radiation model with scalar values from large eddy simulations. Quantitative comparisons of the measured and modeled images of the radiation intensity are shown to be useful for prompting improvements in combustion and radiation models and interpreting distributions of gas temperatures and species concentrations. Good agreement between measured and simulated radiation intensities is observed upstream of the mean stoichiometric flame tip. Differences between measured and simulated radiation intensities near and downstream of the mean stoichiometric flame tip, in regions with low scalar dissipation rates, suggest that including radiation heat loss effects is important even for weakly radiating flames with low radiant heat loss fractions.

1. Introduction

Quantitative comparative studies of measured and computed images provide a useful non-intrusive approach for studying reacting and non-reacting flows and prompting improvements in combustion and radiation models. Computational flow imaging allows results from theoretical calculations to be displayed in a format that mimics experimental observations [1]. Volume rendering is one technique for creating two-dimensional images from three-dimensional discretely sampled computations or measurements [2-5]. The capability to visualize three-dimensional time-dependent results of reacting flow simulations has been advanced by the development of the Fire Dynamics Simulator and Smokeview programs [6]. Smokeview has made the results from reacting flow simulations more accessible by displaying two and three-dimensional temperature and gas species concentration distributions, velocity fields, particle paths, and smoke clouds in an effective manner that allows further insights to be gained [6]. Solid body rotation and false coloring techniques have been used to compute qualitative visible images of sooting laminar diffusion flames [7, 8]. The studies demonstrated that the comparison of computed and measured visible photographs was useful for qualitatively 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 unique size and shape of the flames and important differences in the flame stabilization region suggesting improvements in soot formation and heat loss models [9].

for calculating instantaneous realizations of radiation intensity from spatially and temporally correlated scalar values with an emphasis on turbulent jet flames and pool fires. Viskanta [15] reviewed techniques (including the differential approximation, discrete ordinates, discrete transfer, and finite volume methods) for solving the radiative transfer equation as applied to combustion environments. Coelho [16] reviewed the use of direct numerical simulations, stochastic methods, Reynolds averaged Navier-Stokes simulations, and large eddy simulations to account for turbulence radiation interactions in reacting flows.

A range of computational models have been developed to quantify the effects of scalar fluctuations on radiation transfer within and from turbulent flames. Mazumder and Modest [17] and Li and Modest [18] developed a composition probability density function (PDF) method to study the effects of turbulence radiation interactions in methane/air diffusion flames and bluff-body stabilized flames. In both cases, the peak flame temperature was lower (90 - 100 K) and the total radiation heat loss was higher (30 - 50%) when TRI were included. Li and Modest [19] utilized a similar composition PDF method to investigate the effects of TRI and optical thickness in piloted methane/air jet diffusion flame. Including radiation decreased the calculated peak flame temperature (60 - 330 K) with larger temperature decreases corresponding to the larger optical thickness values. Including TRI further decreased the calculated peak flame temperature (20 - 120 K). Therefore, TRI account for approximately one-third of the temperature decrease caused by radiation. Radiation caused larger temperature decreases for locations downstream of the peak temperature location. Few studies have investigated radiation transfer in the plume region important for many practical applications such as the interaction of hot combustion products with turbine components and the transfer of pollutant emissions to the environment.

Composition probability density function methods [12, 18, 19], direct numerical simulations [20, 21], and large-eddy simulations [22] have been used to study the relative importance of emission and absorption on TRI. In an idealized nonpremixed system, the contributions of the temperature self-correlation, absorption coefficient-Planck function correlation, and absorption coefficient-intensity correlation were found to be important with the relative significance depending on the optical thickness [20]. Emission TRI has been shown to be important at all optical thicknesses while the effects of absorption TRI increase with optical thickness in a turbulent planar channel flow [22].

The effects of turbulence radiation interactions in large eddy simulations and the relative importance of subgrid-scale (SGS) and resolved scale fluctuations have been receiving increased attention over the last few years [23-29]. Coelho [24] concluded that neglecting the effects of TRI in large eddy simulations results in lower errors in comparison to those associated with Reynolds-averaged Navier-Stokes calculations. The effects of SGS TRI in homogeneous isotropic turbulence have been studied using direct numerical simulation and large eddy simulation [25, 26]. The work suggested that the SGS radiation emission (7% of mean resolved radiation emission) should be considered, and the SGS radiation absorption (0.4% of mean resolved radiation absorption) can be neglected for homogeneous isotropic turbulence. The largest contribution to the filtered radiation emission and absorption terms resulted from the large scales. The most significant SGS correlations were found to be the temperature self-correlation and the absorption coefficient-temperature correlation. These two correlations have opposite effects, and the work suggested that neglecting TRI in LES results in good predictions. The combined effect of the SGS correlations leads to an error in the filtered radiation intensity of approximately 5% when the mean temperature is equal to 1500 K, the temperature turbulence intensity is 20%, and the implicit filter is located at the inertial range of the kinetic energy spectrum.

The effects of turbulence radiation interactions in large-eddy simulations of nonluminous and luminous nonpremixed jet flames have been investigated using filtered density function, photon Monte Carlo, and line-by-line models [28]. The work found that the subgrid-scale fluctuations contribute more to emission TRI than the resolved scale fluctuations for LES in which approximately 84% of the turbulence kinetic energy is resolved. Therefore, including a subgrid-scale model for emission TRI is important for flames in which emission TRI is significant. The contribution of subgrid-scale fluctuations to absorption TRI is negligible in comparison to the contribution of the resolved scale fluctuations. Therefore, subgrid-scale absorption TRI can be neglected.

The design of turbulent flame experiments with a range of operating conditions and a range of infrared radiation intensity measurements with adequate spatial and temporal resolution is needed to match the depth and breadth of the numerical parametric studies described here. The present work provides quantitative time-dependent and time-averaged images of the infrared radiation intensity from a representative turbulent nonpremixed flame. The quantitative images offer benchmark data which is useful for suggesting improvements in resolved and unresolved scale models and large eddy simulations. The present work focuses on developing complementary numerical methods for rendering model-based images of the infrared radiation intensity for comparison with the measured images.

Motivated by the previous discussion, the specific objectives of this work are as follows:

1. Develop experimental and numerical methods for quantitatively comparing measured and modeled time-dependent and time-averaged images of the infrared radiation intensity from turbulent flames;
(2) Measure quantitative images of the radiation intensity from a representative turbulent nonpremixed flame defined by the International Workshop on Measurement and Computation of Turbulent Non-premixed Flames (TNF Workshop) to provide benchmark data for comparison with large eddy simulations;

(3) Render model-based time-dependent and time-averaged images of the radiation intensity from the turbulent nonpremixed flame using scalar results from large eddy simulations, a narrowband radiation model, and the radiative transfer equation; and

(4) Compare the measured and modeled images and discuss the capability of the large eddy simulation scalar results and inherent sub-grid scale closure models for simulating time-dependent and time averaged images of the radiation intensity.

2. Methods

2.1. Experimental Methods

2.1.1. Experimental Arrangement

A representative turbulent nonpremixed jet flame [30-37] (flame A) from the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames [38] is studied in this work. The turbulent nonpremixed flame is stabilized on a long tube tapered to a sharp edge with a nominal inner diameter \( D \) of 8 mm. The fuel is a mixture of methane (22.1%), hydrogen (33.2%), and nitrogen (44.7%). The burner is surrounded by a co-flow stream with a cross-section of \( 30 \times 30 \text{ cm}^2 \), supplying ambient air at a mean velocity of 0.3 m/s. The jet exit Reynolds number is 15,200, and the stoichiometric flame length is 68 diameters. The total heat release rate of the flame is 23 kW, and the radiant heat loss fraction is approximately 8% [35].

The experimental arrangement and definitions of coordinate systems used for acquiring images of the infrared radiation intensity are illustrated on the left side of Figure 1. The flame (observed) coordinate system \((x, r, \theta)\) is defined with an origin positioned at the center of the burner exit using cylindrical coordinates. The infrared camera (observer) coordinate system \((X, R, Y)\) is defined using Cartesian coordinates. The burner axis and camera are aligned such that the \(x\) and \(X\) axes are parallel.

2.1.2. Experimental Imaging of Radiation Intensity

Quantitative images of the infrared radiation intensity from the turbulent nonpremixed flame are acquired using a high speed infrared camera (FLIR Phoenix) with an indium antimonide (InSb) detector. Figure 2 shows a schematic of the infrared camera field of view (320 by 256 pixels) approximately drawn to scale. The solid lines represent the full-frame field of view, and the dashed lines represent the approximate fraction of the field of view associated with measurements of the flame. The chord-like paths through the flame are parallel to the \(Y\) axis to within less than 10° based on the camera optics and distance from the camera to the flame centerline. Radiation intensity incident on different pixels of the focal plane array can be approximated by parallel rays.

Figure 3 shows a schematic of the infrared camera optical arrangement. The camera is mounted perpendicular to the flame axis (50 cm from the burner center to the camera lens). The measurements are acquired using a lens with a focal length of 25 mm and a relative aperture (i.e. f-number) of 2.3. The optical arrangement results in a spatial resolution of 0.6 mm at the flame centerline and a solid angle of 0.4 milli-steradians associated with each pixel. Radiation intensity incident on each pixel can be approximated by lines-of-sight.

The depth of field of the camera measurements, as defined in Figure 3, is estimated to be 52.5 mm (approximately 6.5 burner diameters) using geometrical optics and the thin lens approximation [39]. The depth of field is sufficiently large for the current measurements based on the optical arrangement used and size of the flame. The depth of field and accuracy of the parallel rays and lines-of-sight approximations should be re-evaluated if the methods described in this work are applied in future work using different optical arrangements.

Three bandpass filters (2.58 +/- 0.03 μm, 2.77 +/- 0.12 μm, and 4.34 +/- 0.10 μm) are positioned between the camera lens and detector to measure the radiation from water vapor and carbon dioxide. The total spectral response for each of the filters is reported in Figure 4. The total spectral responses include the combined effects of transmission losses through the lens and filter and the response of the focal plane array. The infrared camera is calibrated using a high temperature cavity blackbody source placed the same distance from the camera as the flame centerline to compensate for atmospheric absorption of the flame radiation.

Images of the radiation intensity are acquired over the entire flame and beyond by traversing the burner in the vertical direction. At each location, 6400 images are collected to ensure that the turbulence statistics of the radiation intensity are
statistically converged. The camera exposure time (6 – 200 µs) is adjusted for each location to optimize the camera sensitivity (i.e., avoid the non-linear detector response at low signals and avoid detector saturation at high signals). The sampling frequency (325 – 345 Hz) varies slightly depending on the exposure time.

The experimental uncertainty is estimated by measuring the radiation intensity from the high temperature cavity blackbody source on repeated occasions. The measurements are acquired for a range of blackbody radiation intensities using each of the three filters with a range of exposure times. The experimental uncertainty in the radiation intensity measurements is less than 10% (95% confidence) for each of the filter and exposure time combinations. Representative uncertainty bars of 10% are shown in the relevant figures.

The infrared camera measurements are compared with fast infrared array spectroscopy (FIAS) measurements [33-35, 40] of the turbulent nonpremixed flame for diametric paths at select axial locations (x/D = 20, 40, 60). The spectrometer measurements are spectrally integrated and transmission losses through the camera lens and filter as well as the detector response are taken into account. The uncertainty in the FIAS measurements is 10% [33]. There is less than 15% difference between the spectrally integrated spectrometer and infrared camera measurements. This difference is quantitatively similar to the combined effects of the uncertainty in the camera and spectrometer measurements.

2.2. Computational Methods

2.2.1. Large Eddy Simulation of Scalar Values

Scalar values for the turbulent nonpremixed flame are simulated using a low Mach number variable density large eddy simulation code with a flamelet/progress variable combustion model. Details on the large eddy simulation methods and scalar results for the flame have been reported by Ihme et al. [41] and Ihme and Pitsch [42]. The governing equations, combustion model, boundary conditions, and numerical arrangement are summarized here.

The large eddy simulation code solves the instantaneous Favre-filtered conservation equations of mass, momentum, mixture fraction, and reaction progress variable. The flamelet/progress variable combustion model is used to relate all thermochemical values (i.e. temperature, gas species concentrations, and thermochemical properties) to the mixture fraction and progress variable. The Favre-filtered thermochemical values are modeled using a presumed probability density function closure model. The probability density functions of the mixture fraction and progress variable are modeled using beta and Dirac distributions, respectively. The simulations neglect external forces caused by buoyancy, assume unity Lewis number, and neglect heat losses by thermal radiation.

The governing equations are solved on a cylindrical computational domain with the boundary conditions selected to match the experiments. The fuel enters through a central tube (8 mm inner diameter) with a mean bulk velocity of 42.2 m/s. The fuel is a mixture of methane (22.1%), hydrogen (33.2%), and nitrogen (44.7%). The air co-flow surrounding the central tube enters with a mean bulk velocity of 0.3 m/s. The turbulent inlet velocity profile is generated by performing a separate periodic pipe flow simulation and enforcing constant mass flux. A convective outflow boundary condition is used at the outlet boundary, and a slip-free boundary condition is used at the radial boundary.

The cylindrical computational domain is 120D by 40D by 2π in the axial, radial, and azimuthal directions, respectively. The domain is discretized non-uniformly into 320 by 160 by 64 differential control volumes in the axial, radial, and azimuthal directions, respectively, resulting in a total of approximately 3.28 million grid points. The grid is concentrated near the central fuel nozzle and flame centerline and is stretched in the axial and radial directions as reported by Ihme and Pitsch [42].

2.2.2. Model-Based Imaging of Radiation Intensity

Time-dependent and time-averaged model-based images of the radiation intensity from the turbulent nonpremixed flame are rendered using the simulated scalar values, a narrowband radiation model, and the radiative transfer equation. The flame is discretized using cylindrical coordinates consistent with the spatial resolution of the LES results as illustrated in Figure 1. The path lengths associated with the parallel lines-of-sight passing through each differential control volume are calculated using geometrical relationships. The spectral absorption coefficient is calculated using the simulated scalar values and a narrowband radiation model (RADCAL) [43]. The radiation intensity from the lines-of-sight through the flame is calculated using the solution to the radiative transfer equation for non-scattering media,

\[ I = \int_{\lambda_1}^{\lambda_2} \alpha_\lambda I_\lambda(0)e^{-\tau_\lambda}d\lambda + \int_{\lambda_1}^{\lambda_2} \int_0^{\tau_\lambda} \alpha_\lambda I_{b\lambda}(\tau_\lambda')e^{-\tau_\lambda''}d\tau_\lambda''d\lambda, \]  

(1)
where $I_s(0)$ is the intensity at the starting position along the path, $I_{bb}$ is the blackbody spectral intensity, and $\lambda_1$ and $\lambda_2$ are the filter bandwidth limits. The spectral coefficient $(\alpha_s)$ accounts for transmission losses through the lens and filter and for the response of the focal plane array. The spectral optical thickness ($\tau_s$) is defined as [44],

\[ \tau_s = \int_{0}^{s} \kappa_{s} ds, \]  

where $\kappa_s$ is the spectral absorption coefficient and $s$ is the path length. The radiation intensity is calculated by integrating along lines-of-sight through the flame, applying the spectral response of the optics and camera, and integrating over the spectral range of the filter to allow for quantitative comparison with the measured values. An instantaneous image of the radiation intensity is rendered by performing the calculations along multiple parallel, lines-of-sight through the flame consistent with the spatial and temporal resolution of the simulated scalar values.

Instantaneous images of the radiation intensity as observed from multiple angles orthogonal to the flame axis are calculated. The camera position is rotated about the flame axis in the azimuthal direction as schematically illustrated on the right side of Figure 1. The change in camera observer angle is accomplished numerically by rotating the LES scalar results about the flame axis in the azimuthal direction by an angular increment consistent with the angular spatial resolution of the LES results.

3. Results and Discussion

Time-dependent and mean distributions of the LES temperature results are reported to assist with interpreting the simulated images of the radiation intensity. Figure 5 shows simulated temperature distributions on a plane through the centerline of the turbulent nonpremixed flame. The first three panels on the left illustrate representative instantaneous distributions, and the last panel on the right shows the mean distribution. The time between each of the consecutive instantaneous distributions is 2 ms based on the physical time step of the large eddy simulations.

Figure 6 compares measured [38] and simulated mean and root mean square temperature profiles along the flame centerline. The mean measurements and simulations are in good agreement along the flame centerline upstream of the stoichiometric flame length (68 diameters). Near and downstream of the stoichiometric flame length, the simulated mean temperatures are over-predicted in comparison to the measured values. The difference between the simulations and measurements increases with distance downstream of the stoichiometric flame length. A plausible explanation is that the over predicted temperatures are caused by neglecting radiation heat loss effects within the large eddy simulations. Li and Modest [19] have shown that neglecting radiation heat losses results in temperature values that are over predicted by approximately 100 – 150 K at locations downstream of the stoichiometric flame length in nonluminous partially premixed methane/air flames. Ihme and Pitsch [45] have developed a flamelet/progress variable combustion model which considers radiation heat loss effects. The work demonstrated that radiation heat loss effects on the temperature are most significant in regions of the flame where the scalar dissipation rate is low. The observations suggest improvements in the current simulations are needed to accurately predict scalar values downstream of the stoichiometric flame length if the fuel lean plume region is of interest. The improvements should begin with including radiation heat loss effects which are important even for weakly radiating flames such as the one considered here.

Figure 7 compares measured [38] and simulated mean and root mean square radial temperature profiles at select axial locations ($x/D = 20, 40, 60,$ and $80$). The measured and simulated mean radial profiles are in good agreement at 20 and 40 diameters downstream of the burner exit. The simulated mean temperatures are over predicted in comparison to the measurements at 60 and 80 diameters downstream of the burner exit. A plausible explanation is that the over predicted temperature trends are caused by neglecting radiation heat losses as previously discussed.

Figure 8 shows the measured and simulated images of the infrared radiation intensity from the turbulent nonpremixed flame. The top panels illustrate the measured images, and the bottom panels illustrate the simulated images. The first three panels on the left illustrate representative instantaneous images, and the last panel on the right shows the mean image. The time between each of the simulated and measured instantaneous images is 2 ms and 3 ms, respectively. The horizontal white lines shown in the images indicate the field of view associated with the measured images.

The simulated images of the infrared radiation intensity reveal qualitative features that are similar to the measured images. A relatively low intensity region is apparent near the burner exit ($0 \leq x/D \leq 30$) where the line-of-sight paths through the flame are shorter and the path-integrated temperatures are lower. High intensity regions separated by low intensity regions, representative of the mixing between the combustion products and surrounding air, are apparent with increasing distance downstream ($30 \leq x/D \leq 90$). A wrinkled lower intensity region is observed in the shear layer near the flame edge. The flame edge becomes increasingly wrinkled with distance downstream as mixing between the exhaust products and surrounding air becomes more intermittent. In the plume region ($90 \leq x/D \leq 105$), the entrained air
decreases the temperature and gas species concentration and results in a decrease in the radiation intensity. Similar qualitative features are observed in the measured and simulated images for each of the three bandpass ranges of the mid-infrared spectrum examined in this work.

Figure 9 illustrates the simulated mean image of the radiation intensity from the flame with and without the effects of turbulence instantaneous radiation interactions. First, the mean radiation intensity is calculated by temporally averaging 198 instantaneous images of the infrared radiation intensity based on time-dependent scalar values. Second, the mean radiation intensity is calculated using mean scalar values in the narrowband radiation model and radiative transfer equation. The left panel shows the mean image of the instantaneous images simulated using time-dependent scalar values, the middle panel shows the mean image calculated using mean scalar values, and the right panel shows the normalized difference between the two images. The inclusion of TRI results in larger intensity values throughout the flame. The peak mean intensity is approximately 20% larger when including the effects of TRI. The normalized difference between the images of the radiation intensity with and without TRI illustrates that the effects are most significant near the shear layer where normalized fluctuations in the temperature, water vapor, and carbon dioxide are the largest.

Figure 10 shows the measured and simulated mean and normalized root mean square of the infrared radiation intensity from diametric paths through the flame. Mean radiation intensity values are shown based on time-dependent and mean scalar values to quantify the effects of TRI. The measured and simulated mean radiation intensities agree to within 25% between the burner exit and approximately 40 diameters downstream. Near and downstream of the stoichiometric flame length, the simulated radiation intensity is over predicted in comparison to the measured values. The difference between the simulated and measured radiation intensity values increases with distance downstream of 40 diameters. The trend of increasing differences between the measurements and simulations downstream of 40 diameters is consistent with observations based on comparison of the measured and simulated radial temperature profiles.

Figure 10 also shows simulated mean and normalized root mean square infrared radiation intensities calculated based on simulated temperature distributions corrected to match the mean measured temperature distributions. The results indicate that the mean measured and simulated radiation intensities agree to within 30% if the mean measured and simulated temperature distributions agree. The remaining difference between the mean measured and simulated radiation intensities is attributed to the combined effects of differences between the measured and simulated radiating gas species concentrations, limitations associated with the narrowband radiation model, neglecting subgrid-scale TRI, and experimental uncertainty.

Figure 11 and Figure 12 show simulated images of infrared radiation intensity from the turbulent nonpremixed flame as observed from multiple angles orthogonal to the flame axis at one instant in time. In Figure 11, the observer angle difference between the images is 5.625° in the azimuthal direction consistent with the spatial resolution of the large eddy simulations. Significant spatial correlation in the instantaneous radiation intensity is evident in the images when the flame is observed from different angles separated by 5.625°. In Figure 12, the observer angle difference between the images is 22.5° in the azimuthal direction. Significant variation in the instantaneous radiation intensity is apparent in the images when the flame is observed from different positions separated by larger angles.

Figure 13 shows simulated images of infrared radiation intensity from the flame as observed at one instant in time from two angles separated by 180°. The two images on the left show the radiation intensity for the 2.77 +/- 0.12 µm band, and those on the right show the radiation intensity for the 4.34 +/- 0.10 µm band. The images separated by 180° are approximately mirror images of one another, and the infrared radiation emitted by the flame is qualitatively and quantitatively similar when observed from opposite sides of the flame. Similar observations are applicable when the flame is observed from other angles separated by 180°. The observations indicate that the flame is optically thin for these spectral bands (2.77 +/- 0.12 µm and 4.34 +/- 0.10 µm). Subtle differences in the images from the two angles separated by 180° are indicative of radiation absorption effects. The effects of radiation absorption are small for this flame and can be neglected when including radiation heat losses in future simulations of the flame.

4. Conclusions

Model-based images of the infrared radiation intensity from a representative turbulent nonpremixed flame are rendered and compared with measured images in this work. Specific conclusions from the qualitative and quantitative comparison of the modeled and measured images of the infrared radiation intensity are as follows:

(1) The simulated and measured images of the infrared radiation from the turbulent nonpremixed flame display similar qualitative features. The simulated and measured images show high intensity regions separated by low intensity regions characteristic of turbulent mixing between the fuel and entrained air.

(2) The quantitative comparison of the measured and simulated radial profiles of the scalar values and the quantitative comparison of the measured and simulated path-integrated radiation intensities suggest model
improvements are needed in the plume region. The scalar values and infrared radiation intensities are overestimated near and downstream of the stoichiometric flame length suggesting radiation heat loss effects are important even for weakly radiating flames with low radiative heat loss fractions.

3. The instantaneous infrared radiation intensity varies significantly when observed from different angles orthogonal to the flame axis. Images from two angles separated by 180° appear to be mirror images of one another suggesting that radiation absorption is negligible within the flame.

4. The consistency between conclusions based on path integrated infrared radiation intensities and conclusions based on local scalar values demonstrates that the present model-based image rendering approach is useful for improving understanding and prompting advancements in radiation and combustion models. The present approach of quantitatively comparing measured and simulated images of the infrared radiation intensity is a useful complementary strategy to the conventional approach of quantitatively comparing local scalar profiles at a finite number of select locations.

Although observations, decisions, and conclusions based on path-integrated values are utilized and accepted in many fields (e.g. medical imaging, astrophysics, atmospheric sciences, etc.), such techniques have not been fully utilized in combustion applications. This contribution applies a path-integration technique of infrared radiation intensity, demonstrating its potential for complementary model validation of high-fidelity simulations. It is recognized that the quantitative agreement between measured and simulated path integrated values is a necessary but insufficient criterion for the validation of resolved and unresolved scale models. It is recognized that the path-integrated radiation intensity resulting from the radiative transfer equation is a non-unique solution with many integrands (i.e. scalar distributions) potentially resulting in the same integral (i.e. radiation intensity). However even with these limitations, it is submitted that identifying the scalar distributions that satisfy the radiative transfer equation from the infinitely many possible scalar distributions is a useful approach as demonstrated in this work.

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References


Figure 1. Schematic of the experimental arrangement and discrete domain for rendering simulated images of the infrared radiation intensity for the turbulent nonpremixed flame. Note: (x, r, θ) are flame-based (observed) cylindrical coordinates, (x, y, z) are flame-based (observed) Cartesian coordinates, and (X, R, Y) are camera-based (observer) Cartesian coordinates.
Figure 2. Schematic of the infrared camera field of view approximately drawn to scale. The solid lines represent the full-frame field of view, and the dashed lines represent the approximate fraction of the field of view associated with measurements of the flame. The schematic illustrates that the radiation intensity incident on each pixel of the focal plane array can be approximated by parallel rays.

Figure 3. Schematic of the infrared camera optical arrangement. The schematic illustrates that the radiation intensity incident on each pixel of the focal plane array can be approximated by a line-of-sight because of the small solid angle.
Figure 4. Total spectral transmission of the camera optics including the combined effects of the lens, filter, and detector response.
Figure 5. Simulated instantaneous and mean temperature distributions on a plane through the centerline of the flame.

Figure 6. Measured [38] and simulated mean (left) and root mean square (right) temperature profiles along the centerline of the flame.
Figure 7. Measured [38] and simulated mean (left) and root mean square (right) radial temperature profiles for the flame.
Figure 8. Comparison of measured (top) and simulated (bottom) time-dependent and time-averaged images of infrared radiation intensity ($2.77 \pm 0.12 \mu m$) from the flame.
Figure 9. Simulated time-averaged image of infrared radiation intensity (2.77 +/- 0.12 µm) from the flame with (left) and without (middle) turbulence radiation interaction effects. The difference between the images with and without TRI effects is shown on the right.
Figure 10. Measured and simulated time-averaged (left) and normalized root mean square (right) infrared radiation intensity from diametric paths through the flame.
Figure 11. Simulated images of infrared radiation intensity (2.77 +/- 0.12 µm) from the flame as observed at one instant in time from multiple angles (0° – 16.875° by 5.625°) orthogonal to the flame axis.
Figure 12. Simulated images of infrared radiation intensity (2.77 +/- 0.12 µm) from the flame as observed at one instant in time from multiple angles (0° – 157.5° by 22.5°) orthogonal to the flame axis.
Figure 13. Simulated images of infrared radiation intensity (2.77 +/- 0.12 µm on the left and 4.34 +/- 0.10 µm on the right) from the flame as observed at one instant in time from two angles separated by 180°.