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# Influence of turbulence–radiation interactions in laboratory-scale methane pool fires

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The objective of this study is to assess the effects of Turbulence–Radiation Interactions (TRI) on the structure of small-scale pool fires and on the radiative fluxes transferred to surrounding surfaces. Fire-induced flow is modeled by using a buoyancy-modified k-ε model and the Steady Laminar Flamelet (SLF) model coupled with a presumed Probability Density Function (pdf) approach. A 34-kW methane pool fire produced by burner with a diameter of 0.38 m is simulated by neglecting radiation, by considering radiation without TRIs, and by considering radiation with TRIs. Computations carried out with radiation are based on the Full Spectrum Correlated-k (FSCK) method. TRIs are taken into account by considering the Optically-Thin Fluctuation Approximation (OTFA). The mean radiative source term and the mean RTE are then closed by using a presumed pdf of the mixture fraction, scalar dissipation rate, and enthalpy defect. When TRIs are considered predicted flame structure, radiant fraction and radiative fluxes are found in quantitative agreement with the available experimental data. Simulations reveal that TRIs significantly enhance radiative losses and substantially contribute to the drop in temperature due to radiation. TRIs also contribute to reduce turbulence levels and the root mean square (rms) values of temperature fluctuations. In addition radiative heat fluxes on remote targets are found to be considerably higher than those obtained from radiative calculations based on mean properties. Finally different levels of closure for the TRI-related terms are assessed. Model results show that the complete absorption coefficient-Planck function correlation should be considered in order to properly take into account the influence of TRIs on the emission term whereas the effect of absorption coefficient self-correlation on the absorption term is a reduction by about 12% of the radiant fraction.



## 1. Introduction

TRIs are an important issue in problems involving turbulent flames, their modeling being fundamental if accurate predictions of temperature, radiative fluxes [1], and production of pollutants such as NO [2] or soot [3] are desired.

Taking TRIs into account requires the modeling of two terms. The first term, known as 'absorption TRI', represents the nonlinear coupling between incident radiation and the local absorption coefficient. It is the consequence of property fluctuations across the domain and its modeling requires having a detailed knowledge of the instantaneous fields of temperature and species. Absorption TRI is generally neglected by considering the OTFA, i.e. assuming that the local intensity is weakly correlated with the local absorption coefficient. This approximation was found to be valid over a wide range of conditions [1,3–6], with the exception of large-scale sooting flames [7]. The second term, referred to as 'emission TRI', is determined on the basis of local properties only and can be evaluated by using either presumed-pdf approaches [2,6,8–12] or pdf composition methods [3–5,7,13–16]. Li and Modest [14,15] and Habibi et al. [2] isolate and quantify different levels of closure for emission TRI in turbulent methane jet flames and showed that the complete absorption coefficient-Planck function correlation must be considered to obtain a reliable evaluation.

A significant amount of studies considered decoupled fluid flow/radiative transfer calculations by specifying both the temperature and the species concentrations as input data [17–29]. The methodology initiated by Faeth and co-workers [18–25] consisted in solving the instantaneous RTE along a line of sight by using stochastic methods to prescribe the instantaneous scalar data. This model was systematically applied to a vast quantity of fuels burning in still air, considering both non-luminous and luminous flames. The authors established that radiative emission from a flame may be as much as 50–300% higher than would be expected based on

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**Nomenclature**

| | |
|---|---|
| $a$ | weight function for full-spectrum $k$-distribution methods |
| $D$ | burner diameter |
| $I$ | radiative intensity |
| $I_b$ | blackbody intensity (Planck function) |
| $k$ | absorption coefficient variable at reference state or turbulent kinetic energy |
| $k^*$ | absorption coefficient variable at other state |
| $f$ | $k$-distribution function |
| $f_S$ | soot volume fraction |
| $g$ | cumulative $k$-distribution function |
| $g_i$ | ith quadrature points or gravitational acceleration in direction $i$. |
| $G$ | buoyancy production of k |
| $G_{ij}$ | buoyancy production of $\widetilde{u_i''u_j''}$ |
| $h$ | enthalpy |
| $L$ | axial length |
| $N_G$ | number of quadrature points |
| $N_S$ | soot number density per unit mass of mixture |
| $p_d$ | hydrodynamic pressure |
| $P$ | probability density function or shear production of $k$ |
| $\dot{q}_R''$ | radiative flux |
| $\dot{Q}$ | heat release rate (HRR) |
| $\dot{Q}_R$ | net radiative heat loss |
| $r$ | radial coordinate |
| $R$ | radius |
| $T$ | temperature |
| $u$ | velocity |
| $w_i$ | quadrature weights |
| $W$ | molecular weight |
| $x_i$ | mole fraction of species i |
| $X_R$ | enthalpy defect parameter |
| $Y_S$ | soot mass fraction |
| $z$ | axial coordinate |

*Greek*

| | |
|---|---|
| $\chi$ | scalar dissipation rate |
| $\Delta T$ | mean temperature rise ($T-T_\infty$) |
| $\in$ | rate of dissipation of $k$ |
| $\underline{\phi}$ | composition variable vector ($T$, $p$, $x_i$, $f_S$) |
| $\gamma_R$ | fraction of the heat of combustion radiated away from the flame ($\dot{Q}_R/\dot{Q}$) |
| $\eta$ | wavenumber |
| $\varphi$ | general variable |
| $\kappa_\eta$ | spectral absorption coefficient |
| $\kappa_p$ | Planck-mean absorption coefficient |
| $\mu$ | viscosity |
| $\rho$ | density |
| $\dot{\omega}$ | reaction rate |
| $\xi$ | mixture fraction |
| $\xi''^2$ | mixture fraction variance |

*Subscript*

| | |
|---|---|
| 0 | reference state |
| $\infty$ | ambient condition |
| inj | fuel injection |
| g | at a given value for cumulative k-distribution |
| mix | mixture |
| p | Planck |
| R | radiation |
| S | soot |
| t | turbulent |
| $\eta$ | wavenumber |

*Superscript*

| | |
|---|---|
| fl | flamelet |
| $\overline{()}$,$()'$ | Reynolds averaged mean and fluctuating quantity |
| $\widetilde{()}$,$()''$ | Favre averaged mean and fluctuation quantity |

mean values of temperature and absorption coefficient. This approach was also used and extended by other research groups [6,26–30]. As an example Coelho used a stochastic model to demonstrate the accuracy of the OTFA in Sandia's turbulent flame D [6]. Coupled fluid flow/radiative transfer calculations were also carried out [2–5,7–16]. Modest and co-workers [3–5,7] proposed a comprehensive formulation, combining a photon Monte Carlo method with a composition pdf method, which allows an accurate description of both absorption and emission TRI. This model was applied to investigate the influence of TRIs in non-sooting and sooting jet flames. They showed that the absorption TRI is negligible in lab-scale flames as long as soot levels are of the order of few ppm. Supplementary calculations [7]showed that this conclusion does not hold in large-scale flames where absorption TRI can always be neglected in the gas-phase radiation but is of the order of 10% in soot radiation. In addition, the emission TRI in soot radiation was found to be reduced as compared to lab-scale flames, this being the possible consequence of negative temperature-soot-volume fraction correlations.

Among the above-mentioned studies very few were dedicated to the influence of TRIs on turbulent buoyant diffusion flames representative of unwanted fires. Fischer et al. [17] and Klassen et al. [30,31] evidenced the importance of TRIs on the prediction of radiative intensity in pool fires by carrying out decoupled fluid flow/radiative calculations. The computations of Fischer et al. [17] were based on the measured mean temperature, rms values of temperature fluctuations, and species concentration coupled with a prescribed pdf of the temperature. Mean radiation intensities along the axis of a 0.5m-ethanol pool fire were found to be 25–80% higher when TRIs are considered. Klassen et al. [30] carried out calculations of radiative intensities and radiative fluxes in heavily sooting toluene pool fires by using time series of emission soot volume fractions and temperatures. They concluded that the use of mean values of soot volume fraction and temperature may result in an order of magnitude underestimate of radiative intensities and radiative fluxes. Nevertheless, despite these early works, the simulations of buoyant flames traditionally ignored the couplings between radiation and turbulence [32]. A notable exception is the work of Snegirev [33] who model TRIs in a simplified manner: the fluctuations of species concentration were ignored and the gray absorption coefficient and the emission term were expanded into Taylor series around mean temperatures. High order fluctuations were truncated and the truncation error was estimated from two constants adjusted to match experimental radiant fractions and radiative fluxes on remote targets. However no information was reported about the effects of TRIs on flame structure.

The present study focuses on a 34-kW methane pool fire for which radiative heat transfer is dominated by the gas-phase contribution [34]. Its objective is threefold: 1) to assess the influence of TRIs on the pool-fire structure, 2) to quantify their