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Absorption turbulence-radiation interactions in sooting turbulent jet flames

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ABSTRACT

The effects of absorption Turbulence-Radiation Interactions (TRI) on radiative heat transfer are investigated along characteristic diametric paths of three ethylene/air flames using a stochastic space and time series model. The three flames cover a wide range of scales and optical thicknesses. Model results show that the contribution of absorption TRI to the total absorption increases with the optical thickness but remains lower than 10%. Absorption TRI is largely dominated by soot radiation. The cross-correlation between the soot absorption coefficient and the radiative intensity is found to be mainly negative, leading to an overall negative absorption TRI. Finally, the Optically Thin Fluctuation Approximation can be applied to the modeling of turbulent jet flames despite noticeable discrepancies on mean spectrally-integrated radiative intensity for the large-scale optically-thick flame.

1. Introduction

Sooting turbulent flames are encountered in many industrial and natural combustion systems including boilers, furnaces, compartment and wildland fires. In these large-scale systems, radiative heat transfer is often the dominant mode of heat transfer and has to be modeled accurately if reliable predictions of temperature, radiative fluxes, and pollutants emissions (NOx, soot) are desired [1]. Additional complexities in turbulent reactive flows modeling are so-called Turbulence-Radiation Interactions (TRI) [1,2]. These TRI arise from highly nonlinear coupling between fluctuations in scalar structure (temperature, species concentration, soot volume fraction) of the flow with fluctuations of radiative intensity [1,2]. TRI can be then separated into two terms, namely emission TRI, $\langle \kappa_\eta I_{b\eta} \rangle$, and absorption TRI, $\langle \kappa_\eta I_\eta \rangle$. In these expressions, κ_η, I_η and $I_{b\eta}$ are the absorption coefficient, the radiative intensity and the Planck function at wavenumber η, respectively.

Emission TRI depends only on local scalars such as temperature, species mole fractions, soot volume fraction and can be evaluated accurately by using a one-time one-point joint PDF methods [1–16]. In particular, transported PDF approaches provide an exact closure of this term in both non-sooting and sooting flames [4,5,9–16].

The absorption TRI term can be expressed as $\langle \kappa_\eta I_\eta \rangle = \langle \kappa_\eta \rangle \langle I_\eta \rangle + \langle \kappa'_\eta I'_\eta \rangle$. Modelling absorption TRI consists in taking into account the non-linear coupling between fluctuations of the radiative intensity and fluctuations of the absorption coefficient ($\langle \kappa'_\eta I'_\eta \rangle$). The evaluation of this correlation requires to have a detailed knowledge of the instantaneous fields of temperature and radiatively participating species and to solve the RTE over a significant amount of realizations of the flow. Kabashnikov and coworkers [17,18] showed that, if the mean free path for radiation is much larger than the turbulence eddy length scale, then the correlation between the absorption coefficient and radiative intensity may be neglected, leading to $\langle \kappa_\eta I_\eta \rangle \approx \langle \kappa_\eta \rangle \langle I_\eta \rangle$ [17,18]. This approximation is known as the Optically-Thin Fluctuation Approximation (OTFA) and can be applied when $\kappa_\eta L << 1$, where L is the characteristic length scale of turbulent eddies. It was widely used in the modeling of radiative transfer in reacting flows [3,6–8,13–16]. On the other hand, several approaches were developed to take this correlation into account. The first approach was developed by Faeth and co-workers [19–26]. It consisted in using stochastic generations of time series of turbulent scalar fluctuations. These instantaneous values of scalars are used to solve the RTE along line of sights and determine the statistics related to the instantaneous radiative intensity. It was widely used and extended by other research groups [7,27–30]. In particular, Coelho used it to demonstrate the validity of the OTFA in the non-sooting Sandia D flame [7]. These approaches are time-consuming and were usually limited to decoupled radiative transfer calculation. Other approaches were applied to coupled radiative transfer calculation.

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Nomenclature

d_n	inner burner diameter [m]
f_s	soot volume fraction [-]
g	cumulative k-distribution function
g_k	k^{th} quadrature points
I	radiative intensity
I_b	blackbody intensity (Planck function)
k	absorption coefficient variable [m^{-1}] or turbulent kinetic energy [$m^2 \cdot s^{-2}$]
k_s	soot absorptive index [-]
l_e	integral length scale [m]
l_0	Kolmogorov length scale [m]
m_s	complex index of refraction for soot [-]
N_G	number of quadrature points
n_S	soot refractive index [-]
N_{WB}	number of wide bands
Re	Reynolds number [-]
R_f	flame radius [m]
$R(\Delta s)$	spatial correlation [-]
$R(\Delta t)$	temporal correlation [-]
$R(\Delta s, \Delta t)$	two-point, two-time cross-correlation [-]
r	radial coordinate [m]
s	coordinate along the direction of propagation of a radiation beam [m]
T	temperature [K]
t	time [s]
t_e	integral time scale [s]
t_0	Kolmogorov time scale [s]
u_z	axial velocity [$m \cdot s^{-1}$]
w_k	k^{th} quadrature weight
x_i	mole fraction of the i^{th} species [-]
z	axial coordinate [m]
Δs	length of an element along the direction s [m]
Δt	time interval [s]
ε	dissipation rate of the turbulent kinetic energy [$m^2 \cdot s^{-3}$]
η	wavenumber [cm^{-1}]
κ	absorption coefficient [m^{-1}]
τ	flame optical thickness [-]
τ_{le}	eddy optical thickness [-]

Subscript

ad	adiabatic
f	flame
G	gas
gk	k^{th} quadrature point
i, j	directions i or j
OTFA	optically-thin fluctuation approximation
OTA	optically-thin approximation
P	Planck
s	soot
t	turbulent
η	at a given wavenumber

Superscript

i	i^{th} wide band

Operators

$<\phi>$	Reynolds averaged quantity
ϕ'	Reynolds fluctuating quantity

Tessé et al. [12] modelled absorption TRI in the Kent and Honnery (KH) ethylene/air jet diffusion flame. They used a transported one-time one-point composition PDF method to generate randomly a significant amount of optical paths composed of uncorrelated homogenous turbulent structures with sizes equal to the turbulent integral length scale. The RTE was solved along these optical paths by using a Monte Carlo method. Their results indicated that absorption TRI is positive and represents about 9% of the total absorption, approximately. Modest, Haworth and co-workers take advantage of the fact that the transported PDF method based on the Lagrangian Particles Method provides realizations of the flow [9–11]. This allows to model absorption TRI in an exact manner by introducing a particle-based photon Monte Carlo method coupled to the PDF method. Wang et al. [9] found that the OFTA is valid for the Sandia D flame and two other flames derived from the flame D by scaling-up the jet diameter. The same conclusion was drawn by Mehta et al. [10,11] for sooting lab-scale diffusion flames. It should be pointed out that this conclusion is in contrast with that obtained by Tessé et al. [12]. Nevertheless, Mehta et al. found that absorption TRI becomes noticeable with about 6% of the total absorption and is negative when scaling-up the KH flame by a factor of 32. These previous schemes, based on a detailed knowledge of the instantaneous scalars, are time consuming and require advanced RTE solvers such as the particle-based photon Monte Carlo method [31,32]. As a consequence, attempts to derive approximate scheme compatible with arbitrary solvers were also reported in literature. Coelho [33,34] proposed to use a presumed joint PDF of mixture fraction and radiative intensity to close the absorption TRI term. However, the use of this approach in practical problems seems uncertain due to the presence of several unclosed terms in the transport equations required to determine the local PDF. Modest and Mehta [35] proposed a model based on the radiative diffusion approximation to describe absorption TRI for optically-thick eddies.

The objective of this study is twofold: 1) to provide a better understanding of absorption TRI in sooting turbulent jet flames and 2) to assess the limit of validity of the OTFA in these flames. This task is accomplished by applying a stochastic space and time series method to solve instantaneous RTE along characteristic diametric paths crossing the sooting core of three ethylene/air turbulent jet diffusion flames of different scales and covering a wide range of optical thicknesses. The article is organized as follows. The second section presents the theoretical tools used in this study whereas the third section is devoted to the results and discussions. Finally the conclusions drawn from this study are summarized in Section 4.

2. Theory

2.1. Flame configurations

Three turbulent jet ethylene/air diffusion flames are modeled by using the computational model described in details in Refs. [14–16]. It is based on a hybrid flamelet/joint composition PDF. The joint scalar PDF of the mixture fraction, enthalpy defect, and representative soot properties is solved by using a Stochastic Eulerian Field method (SEF). The scalar dissipation rate is assumed to be statistically independent of the other scalars and its PDF is modeled by a Dirac function. Soot production is modeled by a semi-empirical acetylene/benzene-based soot model. Spectral gas and soot radiation is modeled using a wide-band correlated-k model. The OTFA was applied in these simulations. The model was validated by simulating about 20 C1-C3 hydrocarbon lab-scale jet diffusion flames covering a wide range of Reynolds numbers, fuel sooting propensity and oxygen index (defined as the volume fraction of oxygen in the oxidizer) [15,16]. Model predictions were found to be in reasonable agreement with experimental data in terms of flame structure, soot quantities and radiative loss.